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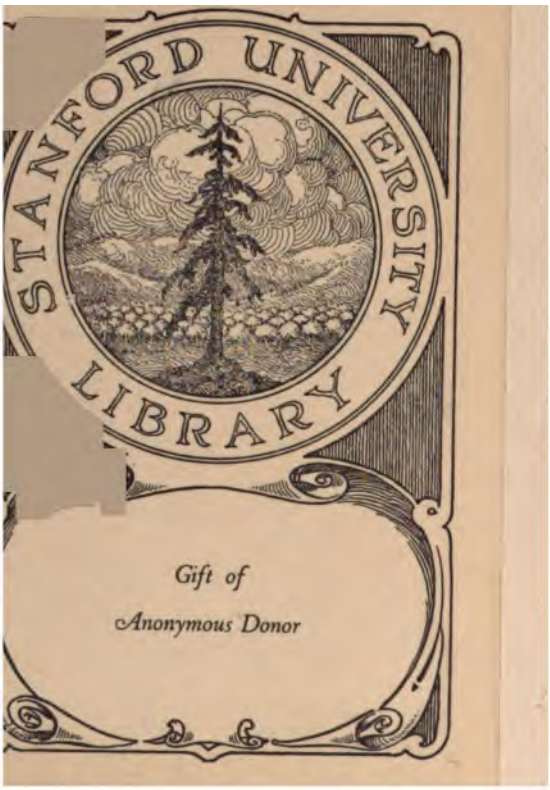
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AN INTRODUCTION TO ASTRONOMY



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FIG. 1. — The Lick Observatory, Mount Hamilton, California.

AN INTRODUCTION

TO

ASTRONOMY

BY

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NEW AND REVISED EDITION

New York
THE MACMILLAN COMPANY
1925

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Set up and electrotyped.
Published April, 1906.
Reprinted August, 1917;
April, 1918; August, 1919;
August, 1920; October,
1921: January, September,
December, 1922;
August, 1924; January,
1925.

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Albert Barnett for the new
with which the book is illus-
Figs. 23 and 30, which were

kindly furnished by Mr. George Otis. He is indebted to Professor David Eugene Smith for photographs of Newton, Kepler, Herschel, Adams, and Leverrier. He is indebted to the Lick, Lowell, Solar, and Yerkes observatories for a large amount of illustrative material which was very generously furnished. He is under deeper obligations to his colleague, Professor W. D. MacMillan, than this brief acknowledgment can express for assistance on the manuscript, on the proofs, and in preparing the many problems which appear in the book.

F. R. MOULTON.

THE UNIVERSITY OF CHICAGO,
September 25, 1916.



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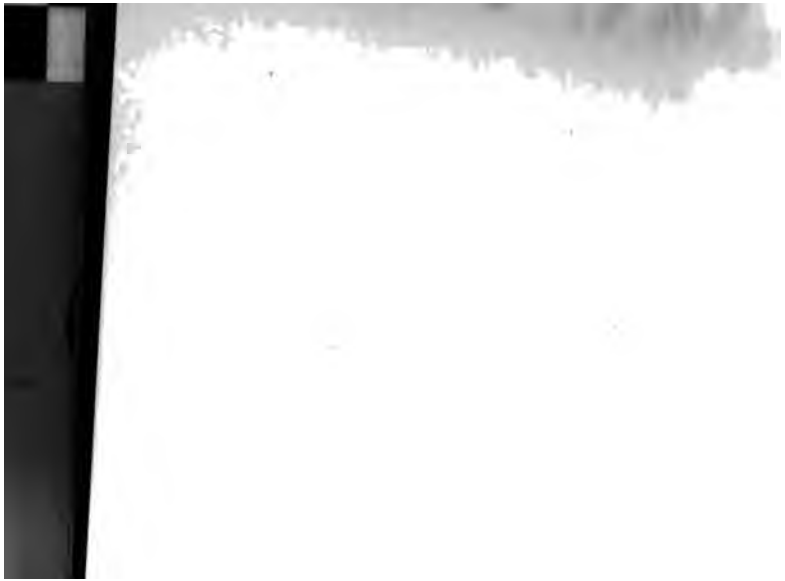
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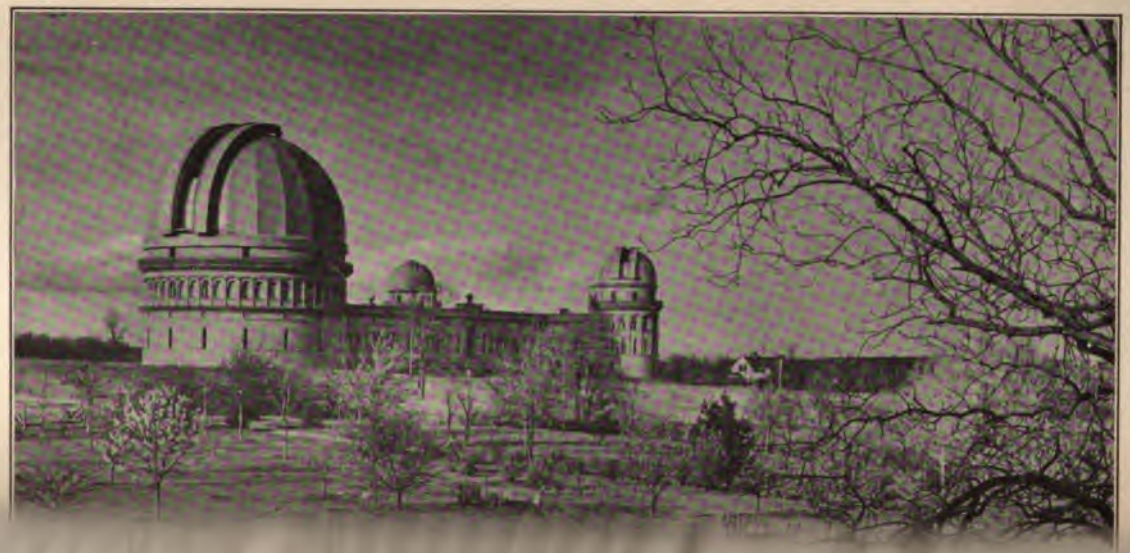
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Astronomy is a science. That is, it is one
jects, such as physics, chemistry, geology,
which have made the present age in very
altogether different from any earlier one. It
oldest science and the parent of a number of
in many respects, it is the most perfect one.
sons it illustrates most simply and clearly the
of science. Consequently, when one enters
of astronomy he not only begins an acqua
subject which has always been noted for its
selfish ideals, but, at the same time, he becom
the characteristics of the scientific movement

2. The Value of Science. — The import
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the leisure it furnishes men.

3. **The Origin of Science.** — It is do
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single man. The great intellectual mov
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were groping for the same truth, withou
before it was fully comprehended.

The foundation on which all science r
that the universe is orderly, and that all
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science was impossible until

acceptance of the term, but it was largely confined to the relations among celestial phenomena. The conception that the heavens are orderly, which they definitely formulated and acted on with remarkable success, has been extended, especially in the last two centuries, so as to include the whole universe. The extension was first made to the inanimate world and then to the more complicated phenomena associated with living beings. Every increase in carefully recorded experience has confirmed and strengthened the belief that nature is perfectly orderly, until now every one who has had an opportunity of becoming familiar with any science is firmly convinced of the truth of this principle, which is the basis of all science.

4. The Methods of Science. — Science is concerned with the relations among phenomena, and it must therefore rest ultimately upon observations and experiments. Since its ideal is exactness, the observations and experiments must be made with all possible precision and the results must be carefully recorded. These principles seem perfectly obvious, yet the world has often ignored them. One of the chief faults of the scientists of ancient times was that they indulged in too many arguments, more or less metaphysical in character, and made too few appeals to what would now seem obvious observation or experiment. A great English philosopher, Francis Bacon (1561–1627), made a powerful argument in favor of founding science and philosophy on experience.

It must not be supposed that the failure to rely on observations and experiment, and especially to record the results of experience, are faults that the world has outgrown. On the contrary, they are still almost universally prevalent among men. For example, there are many persons who believe in dreams or premonitions because once in a thousand cases a dream or a premonition comes true. If they had written down in every case what was expected and what actually happened, the absurdity of their theory would have been evident. The whole mass of superstitions

phenomena has been discovered the next step is to infer, by the process known as induction, that the same thing is true in all similar cases. Then comes the most difficult thing of all. The vital relationships of the one class of phenomena with other classes of phenomena must be discovered, and the several classes must be organized into a coherent whole.

An illustration will make the process clearer than an extended argument. Obviously, all men have observed moving bodies all their lives, yet the fact that a moving body, subject to no exterior force, proceeds in a straight line with uniform speed was not known until about the time of Galileo (1564–1642) and Newton (1643–1727). When the result is once enunciated it is easy to recall many confirmatory experiences, and it now seems remarkable that so simple a fact should have remained so long undiscovered. It was also noted by Newton that when a body is acted on by a force it has an acceleration (acceleration is the rate of change of velocity) in the direction in which the force acts, and that the acceleration is proportional to the magnitude of the force. Dense bodies left free in the air fall toward the earth with accelerated velocity, and they are therefore subject to a force toward the earth. Newton observed these things in a large number of cases, and he inferred by induction that they are universally true. He focused particularly on the fact that every body is subject to a force directed toward the earth.

If taken alone, the fact that bodies are subject to forces toward the earth is not so very important; but Newton used it in connection with many other phenomena. For example, he knew that the moon is revolving around the earth in an approximately circular orbit. At P, in Fig. 3, it is moving in the direction PQ around the earth, E. But it actually moves from P to R. That is, it has fallen toward the earth through the distance QR. Newton perceived that this motion is analogous to that of a body falling near the surface of the earth, or rather to the motion of a body which

bling men to adjust themselves to phenomena over which they have no control. For example, in many harbors large boats can enter or depart only when the tide is high, and the knowledge of the times when the tides will be high is valuable to navigators. After the laws of meteorology have become more perfectly known, so that approaching storms, or frosts, or drouths, or hot waves can be accurately foretold a considerable time in advance, the present enormous losses due to these causes will be avoided.

The knowledge of general laws may lead to information regarding things which are altogether inaccessible to observation or experiment. For example, it is very important for the geologist to know whether the interior of the earth is solid or liquid; and, if it is solid, whether it is elastic or viscous. Although at first thought it seems impossible to obtain reliable information on this subject, yet by a number of indirect processes (Arts. 25, 26) based on laws established from observation, it has been possible to prove with certainty that the earth, through and through, is about as rigid as steel, and that it is highly elastic.

Another important use of the deductive process in science is in drawing consequences of a theory which must be fulfilled in experience if the theory is correct, and which may fail if it is false. It is, indeed, the most efficient means of testing a theory. Some of the most noteworthy examples of its application have been in connection with the law of gravitation. Time after time mathematicians, using this law as a basis for their deductions, have predicted phenomena that had not been observed, and time after time their predictions have been fulfilled. This is one of the reasons why the truth of the law of gravitation is regarded as having been firmly established.

5. The Imperfections of Science. — One of the characteristics of science is its perfect candor and fairness. It would not be in harmony with its spirit to attempt to lead one to suppose that it does not have sources of weakness.

Besides, if its possible imperfections are analyzed, they can be more easily avoided, and the real nature of the final conclusions will be better understood.

It must be observed, in the first place, that science consists of men's theories regarding what is true in the universe about them. These theories are based on observation and experiment and are subject to the errors and incompleteness of the data on which they are founded. The fact that it is not easy to record exactly what one may have attempted to observe is illustrated by the divergence in the accounts of different witnesses of anything except the most trivial occurrence. Since men are far from being perfect, errors in the observations cannot be entirely avoided, but in good science every possible means is taken for eliminating them.

In addition to this source of error, there is another more insidious one that depends upon the fact that observational data are often collected for the purpose of testing a specific theory. If the theory in question is due to the one who is making the observations or experiments, it is especially difficult for him to secure data uninfluenced by his bias in its favor. And even if the observer is not the author of the theory to which the observations relate, he is very apt to be prejudiced either in its favor or against it.

Even if the data on which science is based were always correct, they would not be absolutely exhaustive, and the inductions to general principles from them would be subject to corresponding uncertainties. Similarly, the general principles, derived from various classes of phenomena, which are used in formulating a complete scientific theory, do not include all the principles which are involved in the particular domain of the theory. Consequently it may be imperfect for this reason also.

The sources of error in scientific theories which have been enumerated are fundamental and will always exist. The best that can be done is to recognize their existence and to minimize their effects by all possible means. The fact that

science is subject to imperfections does not mean that it is of little value or that less effort should be put forth in its cultivation. Wood and stone and brick and glass have never been made into a perfect house; yet houses have been very useful and men will continue to build them.

There are many examples of scientific theories which it has been found necessary to modify or even to abandon. These changes have not been more numerous than they have been in other domains of human activities, but they have been, perhaps, more frankly confessed. Indeed, there are plenty of examples where scientists have taken evident satisfaction in the alterations they have introduced. The fact that scientific theories have often been found to be imperfect and occasionally positively wrong, have led some persons who have not given the question serious consideration to suppose that the conclusions of science are worthy of no particular respect, and that, in spite of the pretensions of scientists, they are actually not far removed from the level of superstitions. The respect which scientific theories deserve and the gulf that separates them from superstitions will be evident from a statement of their real nature.

Suppose a person were so situated that he could look out from an upper window over a garden. He could make a drawing of what he saw that would show exactly the relative positions of the walks, shrubs, and flowers. If he were color blind, the drawing could be made in pencil so as to satisfy perfectly all his observations. But suppose some one else who was not color blind should examine the drawing. He would legitimately complain that it was not correct because the colors were not shown. If the colors were correctly given both observers would be completely satisfied. Now suppose a third person should look at the drawing and should then go down and examine the garden in detail. He would find that the various objects in it not only have positions but also various heights. He would at once note that the heights were not represented in the drawing, and a little

them, and in this respect differs from a superstition is not completely in harmony with its own data. It many additional things and leads to their investigation the implications are found to hold true in experience, theory is strengthened; if not, it must be modified. He there should be no reproach in the fact that a scient theory must be altered or abandoned. The necessity such a procedure means that new information has be obtained, not that the old was false.[1]

6. Great Contributions of Astronomy to Science. — A was explained in Art. 3, science started in astronomy. Man astronomical phenomena are so simple that it was possibl for primitive people to get the idea from observing them that the universe is orderly and that they could discover it laws. In other sciences there are so many varying factor that the uniformity in a succession of events would not b discovered by those who were not deliberately looking for it It is sufficient to consider the excessive complexities of th weather or of the developments of plants or animals, to se how hopeless would be the problem which a people with out a start on science would face if they were cut off fro celestial phenomena. It is certain that if the sky had a ways been covered by clouds so that men could not hav observed the regular motions of the sun, moon, and star the dawn of science would have been very much delaye It is entirely possible, if not probable, that without the he of astronomy the science of the human race would yet be a very primitive state.

Astronomy has made positive and important contrib tions to science within historical times. Spherical trig nometry was invented and developed because of its uses determining the relations among the stars on the vault the heavens. Very many things in calculus and still high

[1] The comparison of scientific theories with the picture of the obje seen in the garden is for the purpose of making clear one of their particu features. It must be remembered that in most respects the compari with so trivial a thing is very imperfect and unfair to science.

One of the most important influences in modern thought is the doctrine of evolution. It has not only given direction to investigations and speculations in and geology, but it has also been an important factor interpretation of history, social changes, and even The first clear ideas of the orderly development verse were obtained by contemplating the relations celestial phenomena, and the doctrine of evolution rent in astronomical literature more than half before it appeared in the writings of Darwin, Spencer their contemporaries. In fact, it was carried directly astronomy over into geology, and from geology biological sciences (Art. 242).

7. The Present Value of Astronomy. — From been said it will be admitted that astronomy great importance in the development of science commonly believed that at the present time it practical value to mankind. While its uses means so numerous as those of physics and is nevertheless quite indispensable in a number activities.

Safe navigation of the seas is absolutely dependent astronomy. In all long voyages the captain frequently determine their positions by observing celestial bodies. Sailors use the nautical mile which approximately equals one and one sixth miles. The reason they employ the nautical mile is the distance which corresponds to a change of arc in the apparent positions of the heavenly That is, if, for simplicity, the sun were over the altitude as observed from two vessels a nautical on that meridian would differ by one minute of

Navigation is not only dependent on simple of the sun, moon, and stars, but the mathematical of the motions of these bodies is involved. so difficult and intricate that for a long time

factory measure of time [illegible] very important, conditions under which the [illegible] will make it easier bodies move, and there is [illegible] organized whole all possible to use anything [illegible] in the detailed the apparent motions of [illegible]

Astronomy is, and will [illegible] astronomical object in connection with other [illegible] that are determined fundamental facts on [illegible] entirely or in large of great value to geolo[illegible] part by astronomical information respecting [illegible] means are properly of the earth, it determi[illegible] regarded as belonging earth, it measures the [illegible] to astronomy. tant facts respecting [illegible] Among them are the It is valuable in phy[illegible] shape and size of is a great laborator[illegible] the earth, its average be brought to a co[illegible] density, the condition investigator. For [illegible] of its interior, the ture than can be [illegible] height of its atmosearth. The mater[illegible] phere, its rotation on descent state, and [illegible] its axis and revolproved the existe[illegible] tion around the sun, elements which [illegible] and the climatic conditheir discovery [illegible] ditions of its surface It seems probab[illegible] so far as they are times in the [illegible] determined by its recontain mater[illegible] lation to the sun. than any kno[illegible] The nearest celesby these obje[illegible] tial body is the theories respe[illegible] moon. Astronomers

Astronomy [illegible] the same methods as those an intellect[illegible] that its distance from the earth wonderful [illegible] miles, that its diameter is about in it. Its [illegible] its mass is about one eighteenth that of produced [illegible] holds the moon in its orbit by its gravicountries, [illegible] the moon in turn causes the tides on the not appl[illegible] there is neither atmosphere nor water

on the moon, and the telescope shows that its surface is covered with mountains and circular depressions, many of great size, which are called craters.

The earth is one of the eight planets which revolve around the sun in nearly circular orbits. Three of them are smaller than the earth and four are larger. The smallest, Mercury, has a volume about one twentieth that of the earth, and the largest, Jupiter, has a volume about one thousand times that of the earth. The great sun, whose mass is seven hundred times that of all of the planets combined, holds them in their orbits and lights and warms them with its abundant rays. Those nearest the sun are heated much more than the earth, but remote Neptune gets only one nine-hundredth as much light and heat per unit area as is received by the earth. Some of the planets have no moons and others have several. The conditions on one or two of them seem to be perhaps favorable for the development of life, while the others certainly cannot be the abode of such life as flourishes on the earth.

In addition to the planets, over eight hundred small planets, or planetoids, and a great number of comets circulate around the sun in obedience to the same law of gravitation. The orbits of nearly all the small planets lie between the orbits of Mars and Jupiter; the orbits of the comets are generally very elongated and are unrelated to the other members of the system. The phenomena presented by the comets, for example the behavior of their tails, raise many interesting and puzzling questions.

The dominant member of the solar system is the sun. Its volume is more than a million times that of the earth, its temperature is far higher than any that can be produced on the earth, even in the most efficient electrical furnaces, and its surface is disturbed by the most violent storms. Often masses of this highly heated material, in volumes greater than the whole earth, move along or spout up from its surface at the rate of several hundreds miles a minute.

Many stars, instead of being single isolated masses, like the sun, are found on examination with highly magnifying telescopes to consist of two suns revolving around their common center of gravity. In most cases the distances between the two members of a double star is several times as great as the distance from the earth to the sun. The existence of double stars which may be much closer together than those which are visible through telescopes has also been shown by means of instruments called spectroscopes. It has been found that a considerable fraction, probably one fourth, of all the nearer stars are double stars. There are also triple and quadruple stars; and in some cases thousands of suns, all invisible to the unaided eye, occupy a part of the sky apparently smaller than the moon. Even in such cases the distances between the stars are enormous, and such clusters, as they are called, constitute larger and more wonderful aggregations of matter than any one ever dreamed existed before they were revealed by modern instruments.

While the sun is the center around which the planets and comets revolve, it is not fixed with respect to the other stars. Observations with both the telescope and the spectroscope prove that it is moving, with respect to the brighter stars, approximately in the direction of the brilliant Vega in the constellation Lyra. It is found by use of the spectroscope that the rate of motion is about 400,000,000 miles per year. The other stars are also in motion with an average velocity of about 600,000,000 miles per year, though some of them move much more slowly than this and some of them many times faster. One might think that the great speed of the sun would in a century or two so change its relations to the stars that the appearance of the sky would be entirely altered. But the stars are so remote that in comparison the distance traveled by the sun in a year is negligible. When those who built the pyramids turned their eyes to the sky at night they saw the stars grouped in constellations almost

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QUESTIONS

...ways as possible in which science is

...ental basis on which science rests, and
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... Give examples. Can a science be de-
...ons? Are inductions always true?
... Give examples. Can a science be de-
...ons? Are deductions always true?
... may science be imperfect? How may its im-
...rely eliminated? Are any human activities

...erstition and show in what respects it differs
...ions.
... originate in astronomy?

8. Are conclusions in astronomy firmly established, as they are in other sciences?

9. In what fundamental respects do scientific laws differ from civil laws?

10. What advantages may be derived from a preliminary outline of the scope of astronomy? Would they hold in the case of a subject not a science?

11. What questions respecting the earth are properly regarded as belonging to astronomy? To what other sciences do they respectively belong? Is there any science which has no common ground with some other science?

12. What arts are used in astronomy? Does astronomy contribute to any art?

13. What references to astronomy in the sacred or classical literatures do you know?

14. Has astronomy exerted any influence on philosophy and religion? Have they modified astronomy?

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one of the most important and interesting
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I. QUESTIONS

1. Enumerate as many ways as possibl
beneficial to men.

2. What is the fundamental basis on w
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3. What is induction? Give examples.
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4. What is deduction? Give examples
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5. In what respects may science be impe
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perfect?

6. Name some superstition and show i
from scientific conclusions.

7. Why did science originate in ast

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These lines are respectively perpendicular to CO_1 and CO_2. Therefore the angle between them equals the angle a. That is, the distance traveled is proportional to the change of direction of the plane of the horizon.

The plumb lines at O_1 and O_2 are respectively O_1Z_1 and O_2Z_2, and the angle between these lines is a. Hence the distance traveled is proportional to the change in the direction of the plumb line.

It will be shown now that if the surface of the earth were not a true sphere the change in the direction of the plane of the horizon would not be proportional to the distance traveled on the surface. Suppose Fig. 6 represents a plane section through the non-spherical earth along whose surface the observer travels. Since the earth is not a sphere, the curvature of its surface will be different at different places. Suppose that O_1O_2 is one of the flatter regions and O_3O_4 is one of the more convex ones.

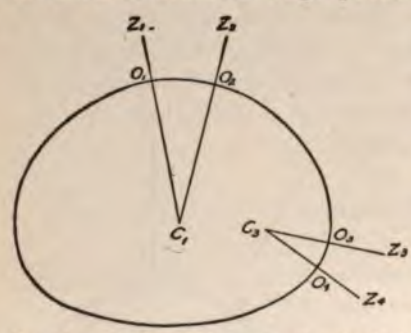


FIG. 6. — If the earth were not spherical, equal angles would be subtended by arcs of different lengths.

In the neighborhood of O_1O_2 the direction of the plumb line changes slowly, while in the neighborhood of O_3O_4 its direction changes more rapidly. The large arc O_1O_2 subtends an angle at C_1 made by the respective perpendiculars to the surface which exactly equals the angle at C_3 subtended by the smaller arc O_3O_4. Therefore in this case the change in direction of the plumb line is *not* proportional to the distance traveled, for the same angular change corresponds to two different distances. The same result is true for the plane of the horizon because it is always perpendicular to the plumb line.

Since the conditions of the statement would be satisfied

in case the earth were spherical, and only in case it were spherical, the next question is what the observations show. Except for irregularities of the surface, which are not under consideration here, and the oblateness, which will be discussed in Art. 12, the observations prove absolutely that the change in direction of the plumb line is proportional to the arc traversed.

Two practical problems are involved in carrying out the proof which has just been described. The first is that of measuring the distance between two points along the sur-

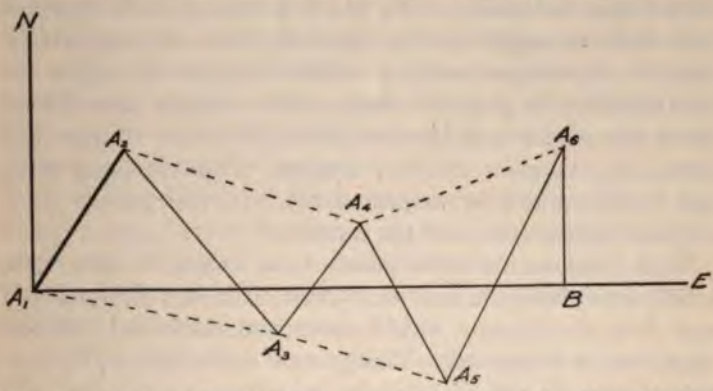


FIG. 7. — The base line A_1A_2 is measured directly and the other distances are obtained by triangulation.

face of the earth, and the second is that of determining the change in the direction of the plumb line. The first is a refined problem of surveying; the second is solved by observations of the stars.

All long distances on the surface of the earth are determined by a process known as triangulation. It is much more convenient than direct measurement and also much more accurate. A fairly level stretch of country, A_1 and A_2 in Fig. 7, a few miles long is selected, and the distance between the two points, which must be visible from each other, is measured with the greatest possible accuracy.

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in part, from the fact that the angles are measured by instruments which magnify them. The fact that the stations are not all on the same level, and the curvature of the earth, introduce little difficulties in the computations that must be carefully overcome.

The direction of the plumb line at the station A_1, for example, is determined by noting the point among the stars at which it points. The plumb line at A_2 will point to a different place among the stars. The difference in the two places among the stars gives the difference in the directions of the plumb lines at the two stations. The stars apparently move across the sky from east to west during the night and are not in the same positions at the same time of the day on different nights. Hence, there are here also certain circumstances to which careful attention must be given in order to get accurate results.

11. Other Proofs of the Earth's Sphericity. — There are many reasons given for believing that the earth is not a plane, and that it is, indeed, some sort of a convex figure; but most of them do not prove that it is actually spherical. It will be sufficient to mention them.

(*a*) The earth has been circumnavigated, but so far as this fact alone is concerned it might be the shape of a cucumber. (*b*) Vessels disappear below the horizon hulls first and masts last, but this only proves the convexity of the surface. (*c*) The horizon appears to be a circle when viewed from an elevation above the surface of the water. This is theoretically good but observationally it is not very exact. (*d*) The shadow of the earth on the moon at the time of a lunar eclipse is always an arc of a circle, but this proof is very inconclusive, in spite of the fact that it is often mentioned, because the shadow has no very definite edge and its radius is large compared to that of the moon.

12. Proof of the Oblateness of the Earth by Arcs of Latitude. — The latitude of a place on the earth is determined by observations of the direction of the plumb line

with respect to the stars. This is the reason that a sea captain refers to the heavenly bodies in order to find his location on the ocean. It is found by actual observations of the stars and measurements of arcs that the length of a degree of arc is longer the farther it is from the earth's equator. This proves that the earth is less curved at the poles than it is at the equator. A body which is thus flattened at the poles and bulged at the equator is called *oblate*.

In order to see that in the case of an oblate body a degree of latitude is longer near the poles than it is at the equator, consider Fig. 8. In this figure E represents a plane section of the body through its poles. The curvature at the equator is the same as the curvature of the circle C_1, and a degree of latitude on E at its equator equals a degree of latitude on C_1. The curvature of E at its pole is the same as the curvature of the circle C_2, and a degree of latitude on E at its pole equals a degree of latitude on C_2. Since C_2 is greater than C_1, a degree of latitude near the pole of the oblate body is greater than a degree of latitude near its equator.

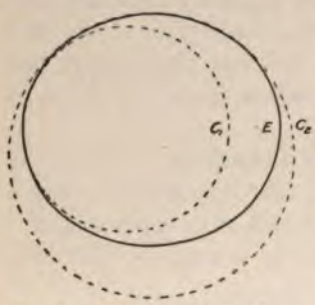


FIG. 8. — The length of a degree of latitude is least at the equator and greatest at the poles.

A false argument is sometimes made which leads to the opposite conclusion. Lines are drawn from the center of the oblate body dividing the quadrant into a number of equal angles. Then it is observed that the arc intercepted between the two lines nearest the equator is longer than that intercepted between the two lines nearest the pole. The error of this argument lies in the fact that, with the exception of those drawn to the equator and poles, these lines are not perpendicular to the surface. Figure 9 shows an oblate body with a number of lines drawn perpendicular

to its surface. Instead of their all passing through the center of the body, they are tangent to the curve AB. The line AE equals the radius of a circle having the same curvature as the oblate body at E, and BP is the radius of the circle having the curvature at P.

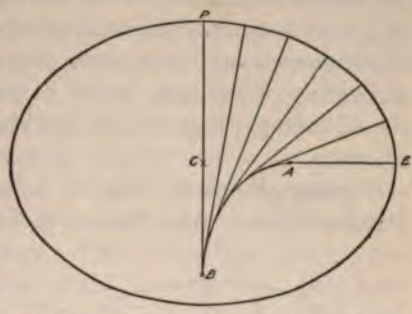


FIG. 9. — Perpendiculars to the surface of an oblate body, showing that equal arcs subtend largest angles at its equator and smallest at its poles.

13. Size and Shape of the Earth. — The size and shape of the earth can both be determined from measurements of arcs. If the earth were spherical, a degree of arc would have the same length everywhere on its surface, and its circumference would be 360 times the length of one degree. Since the earth is oblate, the matter is not quite so simple. But from the lengths of arcs in different latitudes both the size and the shape of the earth can be computed.

It is sufficiently accurate for ordinary purposes to state that the diameter of the earth is about 8000 miles, and that the difference between the equatorial and polar diameters is 27 miles.

The dimensions of the earth have been computed with great accuracy by Hayford, who found for the equatorial diameter 7926.57 miles, and for the polar diameter 7899.98 miles. The error in these results cannot exceed a thousand feet. The equatorial circumference is 24,901.7 miles, and the length of one degree of longitude at the equator is 69.17 miles. The lengths of degrees of latitude at the equator and at the poles are respectively 68.71 and 69.40 miles. The total area of the earth is about 196,400,000 square miles. The volume of the earth is equal to the volume of a sphere whose radius is 3958.9 miles.

14. Newton's Proof of the Oblateness of the Earth. — The first proof that the earth is oblate was due to Newton. He based his demonstration on the laws of motion, the law of gravitation, and the rotation of the earth. It is therefore much more complicated than that depending on the lengths of degrees of latitude, which is purely geometrical. It has the advantage, however, of not requiring any measurements of arcs.

Suppose the earth, Fig. 10, rotates around the axis PP'. Imagine that a tube filled with water exists reaching from the pole P to the center C, and then to the surface on the equator at Q. The water in this tube exerts a pressure toward the center because of the attraction of the earth for it. Consider a unit volume in the part CP at any distance D from the center; the pressure it exerts toward the center equals the earth's attraction for it because it is subject to no other forces. Suppose for the moment that the earth is a sphere, as it would be if it were not rotating on its axis, and consider a unit volume in the part CQ at the distance D from the center. Because of the symmetry of the sphere it will be subject to an attraction equal to that on the corresponding unit in CP. But, in addition to the earth's attraction, this mass of water is subject to the centrifugal force due to the earth's rotation, which to some extent counterbalances the attraction. Therefore, the pressure it exerts toward the center is less than that exerted by the corresponding unit in CP. If the earth were spherical, all units

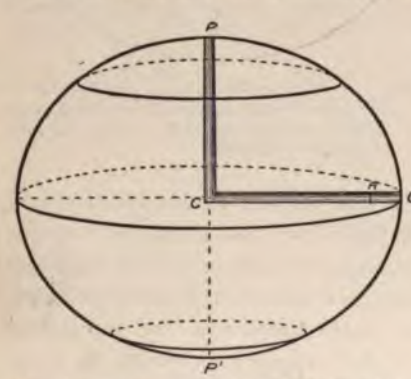


FIG. 10. — Because of the earth's rotation around PP' the column CQ must be longer than PC.

in the two columns could be paired in this way. The result would be that the pressure exerted by PC would be greater than that exerted by QC; but such a condition would not be one of equilibrium, and water would flow out of the mouth of the tube from the center to the equator. In order that the two columns of water shall be in equilibrium the equatorial column must be longer than the polar.

Newton computed the amount RQ by which the one tube must be longer than the other in order that for a body having the mass, dimensions, and rate of rotation of the earth, there should be equilibrium. This gave him the oblateness of the earth. In spite of the fact that his data were not very exact, he obtained results which agree very well with those furnished by modern measurements of arcs.

The objection at once arises that the tubes did not actually exist and that they could not possibly be constructed, and therefore that the conclusion was as insecure as those usually are which rest on imaginary conditions. But the fears aroused by these objections are dissipated by a little more consideration of the subject. It is not necessary that the tubes should run in straight lines from the surface to the center in order that the principle should apply. They might bend in any manner and the results would be the same, just as the level to which the water rises in the spout of a teakettle does not depend on its shape. Suppose the tubes are deformed into a single one connecting P and Q along the surface of the earth. The principles still hold; but the ocean connection of pole and equator may be considered as being a tube. Hence the earth must be oblate or the ocean would flow from the poles toward the equator.

15. Pendulum Proof of the Oblateness of the Earth. — It seems strange at first that the shape of the earth can be determined by means of the pendulum. Evidently the method cannot rest on such simple geometrical principles as were sufficient in using the lengths of arcs. It will be found that it involves the laws of motion and the law of gravitation.

The time of oscillation of a pendulum depends on the intensity of the force acting on the bob and on the distance from the point of support to the bob. It is shown in analytic mechanics that the formula for a complete oscillation is

$$t = 2\pi\sqrt{l/g},$$

where t is the time, $\pi = 3.1416$, l is the length of the pendulum, and g is the resultant acceleration[1] produced by all the forces to which the pendulum is subject. If l is determined by measurement and t is found by observations, the resultant acceleration is given by

$$g = \frac{4\pi^2 l}{t^2}.$$

Consequently, the pendulum furnishes a means of finding the gravity g at any place.

In order to treat the problem of determining the shape of the earth from a knowledge of g at various places on its surface, suppose first that it is a homogeneous sphere. If this were its shape, its attraction would be equal for all points on its surface. But the gravity g would not be the same at all places, because it is the resultant of the earth's attraction and the centrifugal acceleration due to the earth's rotation. The gravity g would be the greatest at the poles, where there is no centrifugal acceleration, and least at the equator, where the attraction is exactly opposed by the centrifugal acceleration. Moreover, the value of g would vary from the poles to the equator in a perfectly definite manner which could easily be determined from theoretical considerations.

Now suppose the earth is oblate. It can be shown mathematically that the attraction of an oblate body for a particle at its pole is greater than that of a sphere of equal volume and density for a particle on its surface, and that at its equator the attraction is less. Therefore at the pole, where

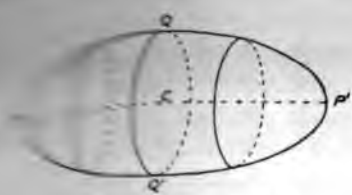
[1] Force equals mass times acceleration. On a large pendulum the force of gravity is greater but the acceleration is the same.

there is no centrifugal acceleration, g is greater on an oblate body than it is on an equal sphere. On the other hand, at the equator g is less on the oblate body than on the sphere both because the attraction of the former is less, and also because its equator is farther from its axis so that the centrifugal acceleration is greater. That is, the manner in which g varies from pole to equator depends upon the oblateness of the earth, and it can be computed when the oblateness is given. Conversely, when g has been found by experiment, the shape of the earth can be computed.

Very extensive determinations of g by means of the pendulum, taken in connection with the mathematical theory, not only prove that the earth is oblate, but give a degree of flattening agreeing closely with that obtained from the measurement of arcs.

The question arises why g is determined by means of the pendulum. Its variations cannot be found by using balance scales, because the forces on both the body to be weighed and the counter weights vary in the same proportion. However, the variations in g can be determined with some approximation by employing the spring balance. The choice between the spring balance and the pendulum is to be settled on the basis of convenience and accuracy. It is obvious that spring balances are very convenient, but they are not very accurate. On the other hand, the pendulum is capable of furnishing the variation of g with almost indefinite precision by the period in which it vibrates. Suppose the pendulum is moved from one place to another where g differs by one hundred-thousandth of its value. This small difference could not be detected by the use of spring balances, however many times the attempt might be made. It follows from the formula that the time of a swing of the pendulum would be changed by about one two-hundred-thousandth of its value. If the time of a complete oscillation were a second, for example, the difference could not be detected in a second; but the deviation for the following second would be equal to

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gravity [illegible]

Of the two oblate spheroids which theory shows are figures of equilibrium for slow rotation, that which is the more nearly spherical is stable, while the other is unstable. That is, if the former were disturbed a little, it would retake its spheroidal form, while if the latter were deformed a little, it would take an entirely different shape, or might even break all to pieces. In spite of the fact that the earth is neither a fluid nor homogeneous, its shape is almost exactly that of the more nearly spherical oblate spheroid corresponding to its density and rate of rotation. This fact might tempt one to the conclusion that it was formerly in a fluid state. But this conclusion is not necessarily sound, because, in such an enormous body, the strains which would result from appreciable departure from the figure of equilibrium would be so great that they could not be withstood by the strongest material known. Besides this, if the conditions for equilibrium were not exactly satisfied by the solid parts of the earth, the water and atmosphere would move and make compensation.

The sun, moon, and planets are bodies whose forms can likewise be compared with the results furnished by theory. Their figures agree closely with the theoretical forms. The only appreciable disagreements are in the case of Jupiter and Saturn, both of which are more nearly spherical than the corresponding homogeneous bodies would be. The reason for this is that these planets are very rare in their outer parts and relatively dense at their centers. It is probable that they are even more stable than the corresponding homogeneous figures.

17. Different Kinds of Latitude. — It was seen in Art. 12 that perpendiculars to the water-level surface of the earth, except on the equator and at the poles, do not pass through the center of the earth. This leads to the definition of different kinds of latitude.

The geometrically simplest latitude is that defined by a line from the center of the earth to the point on its surface

that in the first, and the difference would b
effect would accumulate, second after secon
of 86,400 seconds it would amount to nea
second, a quantity which is easily measur
the difference would amount to about 4
important point in the pendulum method
of the quantities to be measured accumul
come observable.

16. The Theoretical Shape of the Earth. of the earth is not an accident; its sha
size, mass, distribution of density, and ra

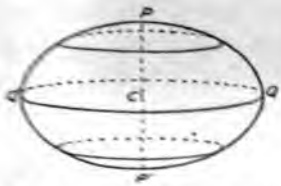


FIG. 11. — Oblate spheroid.



FIG. 12 —

it were homogeneous, its shape could b
mined without great difficulty. It h
mathematical discussions that if a hom
is slowly rotating it may have either
librium, one of which is nearly spheri
very much flattened like a discus. T
simply oblate, but they are figures kn
spheroid is a solid generated by the
(Art. 53) about one of its diameters.
spheroid generated by the rotation
about its shortest diameter PP'. I
circumference. Figure 12 is a *prol*
by the rotation of the ellipse $PQP'Q'$
eter PP'. The equator of this fi
cumference. The oblate and
mentally different in shape.

earthen and they finally agreed with the conclusion of Newton. They extended the arc that Picard had started from the Pyrenees to Dunkirk, an angular distance of 9°. The results were published in 1720. They sent an expedition to Peru, on the equator, in 1735, under Bouguer, Condamine, and Godin. By 1745 these men had measured an arc of 3°. In the meantime an exp[illegible]apland, near the Arctic circle, had measured ar[illegible] On comparing these measurements it was fo[illegible] degree of latitude is greater the farther it is fr[illegible]uator.

In the last century all [illegible]ncipal governments of the world have carried out ve[illegible]ive and accurate surveys of their possessions. The[illegible]nave not only triangulated the British Isles but they have done an enormous amount of work in India and Africa. The Coast and Geodetic Survey in the United States has triangulated with unsurpassed precision a great part of the country. They have run a level from the Atlantic Ocean to the Pacific. The names most often encountered in this connection are Clarke of England, Helmert of Germany, and Hayford of the United States. Hayford has taken up an idea first thrown out by the English in connection with their work in India along the borders of the Himalaya Mountains, and by using an enormous number of observational data and making appalling computations he has placed it on a firm basis. The observations in India showed that under the Himalaya Mountains the matter is not as dense as it is under the plains to the south. Hayford has proved that the corresponding thing is true in the United States even in the case of very moderate elevations and depressions. Moreover, deficiency in density under the elevated places is just enough to offset the elevations so that the total weight of the material along every radius from the surface of the earth to its center is almost exactly the same. This theory is known as the theory of isostasy, and the earth is said to be in almost perfect isostatic adjustment.

II. QUESTIONS

1. In order to prove the sphericity of the earth by measurement of arcs, would it be sufficient to measure only along meridians? (Consider the anchor ring.)

2. Do the errors in triangulation accumulate with the length of the distance measured? Do the errors in the astronomical determination of the angular length of the arc increase with its length?

3. How accurately must a base line of five miles be measured in order that it may not introduce an error in the determination of the earth's circumference of more than 1000 feet?

4. Which of the reasons given in Art. 11 actually prove quantitatively that the earth is spherical? What other reasons are there for believing it is spherical?

5. The acceleration g in mid-latitudes is about 32.2 feet per second; how long would a pendulum have to be to swing in 1, 2, 3, 4 seconds?

6. Draw to scale a meridian section of a figure having the earth's oblateness.

7. Newton's proof of the earth's oblateness depends on the knowledge that the earth rotates; what proofs of it do not depend upon this knowledge?

8. Suppose time can be measured with an error not exceeding one tenth of a second; how accurately can g be determined by the pendulum in 10 days?

9. Suppose the solid part of the earth were spherical and perfectly rigid; what would be the distribution of land and water over the surface?

10. Is the astronomical latitude greater than, or equal to, the geocentric latitude for all points on the earth's surface?

11. What distance on the earth's surface corresponds to a degree of arc, a minute of arc, a second of arc?

12. Which of the proofs of the earth's sphericity depend upon modern discoveries and measurements?

II. The Mass of the Earth and the Condition of its Interior

19. The Principle by which Mass is Determined. — It is important to understand clearly the principles which are at the foundation of any subject in which one may be interested, and this applies in the present problem. The ordinary method of determining the mass of a body is to weigh it.

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20. The Mass and Density of the Earth. — By applications (Arts. 21, 22) of the principle in Art. 19 the mass of the earth has been found. If it were weighed a small quantity at a time at the surface, its total weight in tons would be 6×10^{21}, or 6 followed by 21 ciphers. This makes no appeal to the imagination because the numbers are so extremely far beyond all experience. A much better method is to give its density, which is obtained by dividing its mass by its volume. With water at its greatest density as a standard, the average density of the earth is 5.53.

The average density of the earth to the depth of a mile or two is in the neighborhood of 2.75. Therefore there are much denser materials in the earth's interior; their greater density may be due either to their composition or to the great pressure to which they are subject. The density of quartz (sand) is 2.75, limestone 3.2, cast iron 7.1, steel 7.8, lead 11.3, mercury 13.6, gold 19.3, and platinum 21.5. It follows that no considerable part of the earth can be composed of such heavy substances as mercury, gold, and platinum, but, so far as these considerations bear on the question, it might be largely iron.

The distribution of density in the earth was worked out over 100 years ago by Laplace on the basis of a certain assumption regarding the compressibility of the matter of which it is composed. The results of this computation have been compared with all the phenomena on which the disposition of the mass of the earth has an influence, and the results have been very satisfactory. Hence, it is supposed that this law represents approximately the way the density of the earth increases from its surface to its center. According to this law, taking the density of the surface as 2.72, the densities at depths of 1000, 2000, 3000 miles, and the center of the earth are respectively 5.62, 8.30, 10.19, 10.87. At no depth is the average density so great as that of the heavier metals.

[illegible] forces. It has been solv[illegible]
[illegible] torsion balance.

[illegible] torsion balance consists essentially
[illegible] in Fig. 14, connected by a rod which

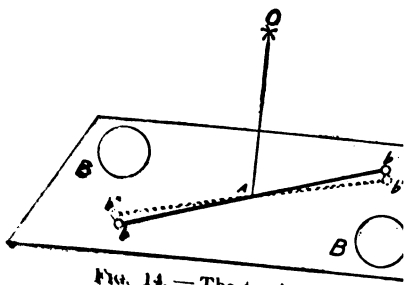


FIG. 14. — The torsion balance.

the point O by a quartz fiber OA. If the [illegible]
for a considerable time in a sealed case so th[illegible]
[illegible] by air currents, it comes to rest. Su[illegible]
[illegible] are at rest and that the large balls B[illegible]
brought near them on opposite sides of the [illegible]
as shown in the figure. They exert slight attr[illegible]
would both and gradually move them agai[illegible]
[illegible] of the quartz fiber to [illegible]

The next problem is to determine from the deflection which the large balls have produced how great the force is which they have exerted. This would be a simple matter if it were known how much resistance the quartz fiber offers to twisting, but the resistance is so exceedingly small that it cannot be directly determined. However, it can be found by a very interesting indirect method.

Suppose the large balls are removed and that the rod connecting the small balls is twisted a little out of its position of equilibrium. It will then turn back because of the resistance offered to twisting by the quartz fiber, and will rotate past the position of equilibrium almost as far as it was originally displaced in the opposite direction. Then it will return and vibrate back and forth until friction destroys its motion. It is evident that the characteristics of the oscillations are much like those of a vibrating pendulum. The formula connecting the various quantities involved is

$$t = 2\pi\sqrt{l/f},$$

where t is the time of a complete oscillation of the rod joining b and b, l is the distance from A to b, and f is the resistance of torsion. This equation differs from that for the pendulum, Art. 15, only in that g has been replaced by f. Now l is measured, t is observed, and f is computed from the equation with great exactness however small it may be.

Now that f and g are known it is easy to compute the mass of the earth by means of the law of gravitation (Art. 146). Let E represent the mass of the earth, R its radius, $2B$ the mass of the two large balls, and r the distances from BB to bb respectively. Then, since gravitation is proportional to the attracting mass and inversely as the square of its distance from the attracted body, it follows that

$$\frac{E}{R^2} : \frac{2B}{r^2} = g : f.$$

In this proportion the only unknown is E, which can therefore be computed.

22. Determination of the Density of the Earth by the Mountain Method. — The characteristic of the torsion balance is that it is very delicate and adapted to measuring very small forces; the characteristic of the mountain method is that a very large mass is employed, and the forces are large. In the torsion balance the balls BB are brought near them, suspended by the quartz fiber and are removed again. The mountain cannot be moved, and the advantage of using a large mass is at least partly counterbalanced by the difficulties. The necessity for moving the attracting body (in this case the mountain) is obviated in a very ingenious manner.



The mountain method of determining the mass of the earth.

For simplicity let the oblateness of the earth be neglected in explaining the mountain method. In Fig. 15, C is the center of the earth, M is the mountain, and O_1 and O_2 are two stations on opposite sides of the mountain at which plumb lines are suspended. If it were not for the attraction of the mountain, they would hang in the directions O_1C and O_2C. The angle between these lines at C depends upon the distance between the stations O_1 and O_2. The distance between these stations, though they are on opposite sides of the mountain, can be obtained by triangulation. Then, since the size of the earth is known, the angle at C can be computed.

But the attraction of the mountain for the plumb bobs causes the plumb lines to hang in the directions O_1A and O_2A. The directions of these lines with respect to the stars can easily be determined by observations, and the difference in their directions as thus determined is the angle at A.

What is desired is the deflections of the plumb line produced by the attractions of the mountain. It follows from elementary geometry that the sum of the two small deflections CO_1A and CO_2A equals the angle A minus the angle C. Suppose, for simplicity, that the mountain is symmetrical and that the deflections are equal. Then each one equals one half the difference of the angles A and C. Therefore the desired quantities have been found.

When the deflection has been found it is easy to obtain the relation of the force exerted by the mountain to that due to the earth. Let Fig. 16 represent the plumb line on a large scale. If it were not for the mountain it would hang in the direction O_1B_1; it actually hangs in the direction $O_1B'_1$. The earth's attraction is in the direction O_1B_1, and that of the mountain is in the direction $B_1B'_1$. The two forces are in the same ratio as O_1B_1 is to $B_1B'_1$, for, by the law of the composition of forces, only then would the plumb line hang in the direction $O_1B'_1$.



FIG. 16. — The deflection of a plumb line.

The problem of finding the mass of the earth compared to that of the mountain now proceeds just like that of finding the mass of the earth compared to the balls BB in the torsion-balance method. The mountain plays the rôle of the large balls. A mountain 5000 feet high and broad would cause nearly 800 times as much deflection as that produced by an iron ball a foot in diameter. The advantage of the large deflection is offset by not having very accurate means of measuring it, and also by the fact that it is necessary to determine the mass of a more or less irregular shaped mountain made up of materials which may lack much of

22. Determination of the Density of the Ea
Mountain Method. — The characteristic of
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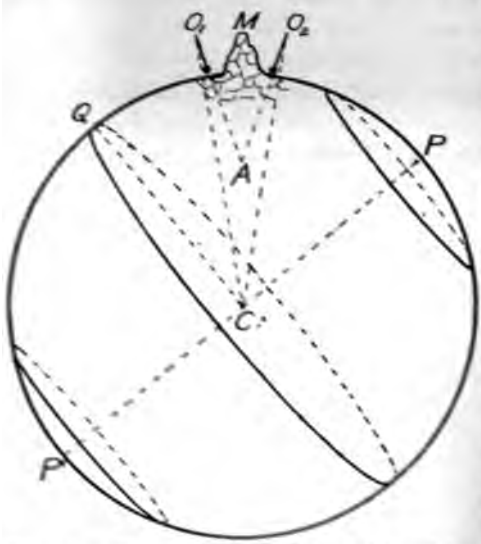


FIG. 13. — The mountain method of determining the mass of the earth.

mountain they would hang in the directi
The angle between these lines at C depends
between the stations O_1 and O_2. The dist
stations, even though they are on opposite
tain, can be obtained by triangulatio
of the earth is known, the angle at

being uniform to ... ly 300 tons, method was the ... the pressure

23. Determin... Pendulum Me... ... and more refined ... is at the earth's pendulum furn... depths depends the force of g... On the basis in using it the ... probably is a good indefinitely; ... per square inch at in the method ... the atmospheric

Suppose a ... tons. earth so long ... creases the boiling rately deter... tly by experiment place down ... of solids. There- is subject w... at moderate depths pendulum w... that its interior is the centrifu... question cannot be diminished ... place, there is no very cause can ... erature, and, in the position a... experiments at such lum will b... several methods of factor also ... gh and through, and will be ... this cau... **sticity of the Earth by** below a ... several lines of attack now be u... ... of the rigidity of the directly ... ... generated in the earth matter, ... satisfactory; and of the found ... by Michelson and carried dulum ... in 1913, has given by far which ... it has settled one very rection ... other method has been able change ... is highly elastic instead of the ma... the work of Michelson pendul... essenti... between a solid and a liquid is of the ... to deforming forces while

the latter does not. If a perfect solid existed, no force whatever could deform it; if a perfect liquid existed, the only resistance it would offer to deformation would be the inertia of the parts moved. Neither perfect solids nor absolutely perfect liquids are known. If a solid body has the property of being deformed more and more by a continually applied force, and if, on the application of the force being discontinued, the body not only does not retake its original form but does not even tend toward it, then it is said to be *viscous*. Putty is a good example of a material that is viscous. On the other hand, if on the application of a continuous force the body is deformed to a certain extent beyond which it does not go, and if, on the removal of the force, it returns absolutely to its original condition, it is said to be *elastic*. While there are no solid bodies which are either perfectly viscous or perfectly elastic, the distinction is a clear and important one, and the characteristics of a solid may be described by stating how far it approaches one or the other of these ideal states.

In order to find how the earth is deformed by forces it is necessary to consider what forces there are acting on it. The most obvious ones are the attractions of the sun and moon. But it is not clear in the first place that these attractions tend to deform the earth, and in the second place that, even if they have such a tendency, the result is at all appreciable. A ball of iron attracted by a magnet is not sensibly deformed, and it seems that the earth should behave similarly. But the earth is so large that one's intuitions utterly fail in such considerations. The sun and moon actually do tend to alter the shape of the earth, and the amount of its deformation due to their attractions is measurable. The forces are precisely those that produce the tides in the ocean.

It will be sufficient at present to give a rough idea, correct so far as it goes, of the reason that the moon and sun raise tides in the earth, reserving for Arts. 263, 264 a more

inch at the depth of 100 miles ... In Fig. 17 let E rep- and at 1000 miles it is 3000 t... the direction toward is not strictly proportional to ... the line from E to means must be employed to find ... The moon is 4000 center. Moreover, the pressur... miles nearer to upon the distribution of mass ... of the moon for of the Laplacian law of density ... approximation to the truth, th... the center of the earth is 3,000 ... pressure at the earth's surface, ...



It is a familiar fact that pr... points of liquids. It has been fo... that pressure increases the melti... fore, in view of the enormous p... in the earth, it is not safe to ... molten without further evidence ... answered directly because, in th... exact means of determining th... second place, it is not possible t... high pressures. There are, ha... proving that the earth is solid ... they will now be considered.

... and S on the earth produced by ...

25. Proof of the Rigidity and ... the Tide Experiment. — Among ... than it is for a unit mass at E, ... at E than it is for one at B. ... earth to the moon is 240,000 that have been made on the qu... from A is fifty-nine sixtieths earth, the one depending on the ... attraction varies inversely by the moon and sun has been m... the force on A is about one methods of this class, that devise... and the difference between out in collaboration with Gale, ... slightly less. the most exact results. Beside... the attraction of the moon important question, which no o... it tends to pull the nearer to answer, namely, that the earth ... of the earth E, and the being viscous. For these reaso... more remote material at B. and Gale will be treated first.

The important difference betw... possible to compute the that the former offers resistance ... if it were a perfect fluid. ... tidal bulges, at A and B.

The concentric lines shown in Fig. 17 are the lines of equal elevation. A rather difficult mathematical discussion shows that the radii EA and EB would each be lengthened by about four feet. Since the earth possesses at least some degree of rigidity its actual tidal elongation is somewhat less than four feet. When it is remembered that the uncertainty in the diameter of the earth, in spite of the many years that have been devoted to determining it, is still several hundred feet, the problem of finding how much the earth's elongation, as a consequence of the rapidly changing tidal forces, falls short of four feet seems altogether hopeless of solution. Nevertheless the problem has been solved.

Suppose a pipe half filled with water is fastened in a horizontal position to the surface of the earth. The water in the pipe is subject to the attraction of the moon. To fix the ideas, suppose the pipe lies in the east-and-west direction in the same latitude as the point A, Fig. 17. Suppose, first, that the earth is absolutely rigid so that it is not deformed by the moon, and consider what happens to the water in the pipe as the rotation of the earth carries it past the point A. When the pipe is to the west of A the water rises in its eastern end, and settles correspondingly in its western end, because the moon tends to make an elevation on the earth at A. When the pipe is carried past A to the east the water rises in its western end and settles in its eastern end. Since the earth is not absolutely rigid the magnitudes of the tides under the hypothesis that it is rigid cannot be experimentally determined; but, since all the forces that are involved are known, the heights the tides would be on a rigid earth can be computed.

Suppose now that the earth yields perfectly to the disturbing forces of the moon. Its surface is in this case always the exact figure of equilibrium. Consider the pipe, which is attached to this surface, when it is to the west of A. The water would be high in its eastern end if the shape of the surface of the earth were unchanged. But the surface to

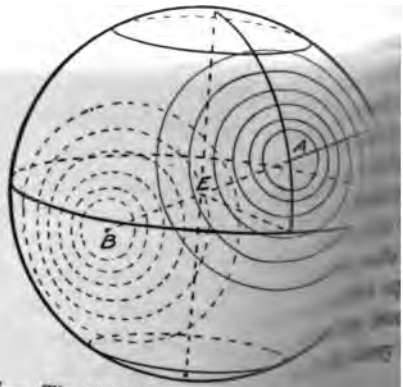


FIG. 17. — The tidal bulges at A and
the moon.

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and greater for a unit mass at
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Now suppose the water rises; ...t from S, the change in their ...change ...distances ...ccurately ...of perma- ...nd the ...level were ...per cent of ...the accuracy ...plicated nature ...be pointed out.

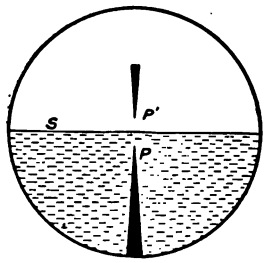


FIG. 18. — End of pipe in the Michelson-Gale tide experiment.

...lges A and B, Fig. 17, which give an idea ...to the water in the pipes. For simplicity, ...on the east-and-west pipe, which in the ex- ...out 13° north of the highest latitude A ever ...uating earth carried it daily across the merid- ...north of A, and similarly across the meridian ...the relations were as represented in the dia- ...ere considerable tides in the pipe before and ...d the meridian at A because it was, so to speak, ...tidal bulge. On the other hand, when it crossed ...n of B about 12 hours later, the tides were very ...cause the bulge B was far south of the equator. ...moon was not all the time north of the plane of the ...quator. Once each month it was 28° north and ...h month 28° south, and it varied from hour to hour ...ther irregular manner. Moreover, its distance, on ...the magnitudes of the tidal forces depend, also changed ...ntinuously. Then add to all these complexities the cor- ...responding ones due to the sun, which are unrelated to those ...of the moon, and which mix up with them and make the ...phenomena still more involved. Finally, consider the north- and-south pipe and notice, by the help of Fig. 17, that its tides are altogether distinct in character from those in the

the east of it is elevated and the pipe is raised with it over, the elevation of the surface is, under the hypothesis, just that necessary for equilibrium. In this case there is no tide at all with respect to the

The actual earth is neither absolutely rigid nor fluid. Consequently the tides in the pipe will neither their theoretical maximum nor zero. The by which they fall short of the value they would earth were perfectly rigid depends upon the exten it yields to the moon's forces, and is a measure of ing. Therefore the problem of finding how much is deformed by the moon is reduced to computing the tides in the pipe would be if the earth were rigid, and then comparing these results with the in the pipe as determined by direct experiment. amount the earth yields has been determined its rigidity can be found by the theory of the of solid bodies.

In the experiment of Michelson and Gale two used, one lying in the plane of the meridian and the east-and-west direction. In order to secure from vibrations due to trains and heavy wagons placed on the grounds of the Yerkes Observa avoid variations in temperature they were buried of feet in the ground. Since the tidal forces are pipes 500 feet long were used, and even then the tides were only about two thousandths of an inch

An ingenious method of measuring these small level was devised. The ends of the pipes were plane glass windows through which their interiors viewed. Sharp pointers, fastened to the pipes just under the surface of the water near the wind viewed from below the level of the water the reflected image could be seen. Figure 18 one of the pipes. S is the surface of the water and P' is its reflected image. The distance

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rth's **Rigidity.** — (*a*) There is
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The perfection of this domain of scien
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unless scientific conclusions respecting al
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in the north-and-south pipe the observe
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of the moon and sun [illegible] of wabbling were that of measuring the [illegible] could be computed. that the position of [illegible] earth's axis of rotation acting on it, and, if [illegible] proves that the of its direction would [illegible] level surface. Con[illegible] **Rigidity of the** to the forces of the [illegible] of attempting to stantly remain per[illegible] starts with Newton, But if the earth did [illegible] not clearly formu- undergo very minu[illegible] determination of mass part analogous to th[illegible] be discovered. By fication of the ordin[illegible] he arrived at the pendulum, was fou[illegible] six times as dense as oscillations, giving [illegible] factory evidence re[illegible] determine the density of

(*b*) The principle [illegible] who used the mountain ing tides in pipes [illegible] found 4.5 for the density Longer columns of [illegible] devised by Michell, was is difficulty in obtai[illegible] England, in 1798. His and very much gr[illegible] obtained by later experi- retical heights on [illegible] mentioned Baily (1840) in would necessarily [illegible] Germany, Cornu (1872) in found possible to p[illegible] Boys (1893) in England, degree of accuracy [illegible] The pendulum method, using been observed. Y[illegible] difference in elevation, ferred on this basi[illegible] of times.

(*c*) Earthquakes [illegible] Thomson) first gave in some restricted regi[illegible] the earth is rigid. His con- ing in intensity [illegible] of the oceanic tides, as out- depending primari[illegible] by means of the rate of pendulum, can de[illegible] gives its possibility largely of thousands of mi[illegible] who long lived in Japan, are of different t[illegible] by earthquakes. His interest rocks around the [illegible] stimulated him to the inven- ocean, while othe[illegible] as seismographs, for detecting sound in the air, [illegible] The change of the posi-

tion of the plane of the earth's equator, known as the precession of the equinoxes, has been known observationally ever since the days of the ancient Greeks, and its cause was understood by Newton, but it has not been used to prove the rigidity of the earth because it takes place very slowly. The wabbling of the axis of the earth was first established observationally, in 1888, by Chandler of Cambridge, Mass., and Küstner of Berlin. The theoretical applications of the rigidity of the earth were made first by Newcomb of Washington, and then more completely by S. S. Hough of England. The first attempt at the determination of the rigidity of the earth by the amount it yields to the tidal forces of the moon and sun was made unsuccessfully in 1879 by George and Horace Darwin, in England. Notable success has been achieved only in the last 15 years, and that by improvements in the horizontal pendulum and by taking great care in keeping the instruments from being disturbed. The names that stand out are von Rebeur-Paschwitz, Ehlert, Kortozzi, Schweydar, Hecker, and Orloff. The observations of Hecker at Potsdam, Germany, were especially good, and Schweydar made two exhaustive mathematical discussions of the subject.

III. QUESTIONS

1. What is the difference between mass and weight? Does the weight of a body depend on its position? Does the inertia of a body depend on its position?

2. Can the mass of a small body be determined from its inertia? Can the mass of the earth be determined in the same way?

3. What is the average weight of a cubic mile of the earth?

4. Discuss the relative advantages of the torsion-balance method and mountain method in determining the density of the earth. Which one has the greater advantages?

5. What is the pressure at the bottom of an ocean six miles deep?

6. Discuss the character of the tides in east-and-west and north-and-south pipes during a whole day when the moon is in the position indicated in Fig. 17, and when it is over the earth's equator.

... advantages and disadvantages of a long pipe

... Fig. 17. Is its weight greater or less than ... spring balances? By balance scales?

... 5.

... the theories and facts involved in the

... which the several proofs of the earth's ... fundamentally different methods are ...

The Earth's Atmosphere

... and Mass of the Earth's Atmosphere. — ... gaseous envelope which surrounds ... constituents are the elements nitrogen ... are also minute quantities of argon, ... hence, and some other very rare con- ... by volume at the earth's sur- ... atmosphere is nitrogen, 21 per cent ... argon, and the remaining elements ... quantities.

... are elements; that is, they are ... not broken up into more fundamental ... any chemical changes. The thou- ... that are found on the earth are ... elements, only about half of which ... occurrence. The union of elements ... and is a very fundamental matter, for ... have properties very unlike those of any ... which it is composed. For example, ... and nitrogen are in almost all food, but ... which is composed of these elements alone,

... elements which have been enumerated, the ... contains some carbon dioxide, which is a com- ... and oxygen, and water vapor, which is ... oxygen and hydrogen. In volume three

hundredths of one per cent of the earth's atmosphere is carbon dioxide; but this compound is heavier than nitrogen and oxygen, and by weight, 0.05 per cent of the atmosphere is carbon dioxide. The amount of water vapor in the air varies greatly with the position on the earth's surface and with the time. There are also small quantities of dust, soot, ammonia, and many other things which occur in variable quantities and which are considered as impurities.

The pressure of the atmosphere at sea level is about 15 pounds per square inch and its density is about one eight-hundredth that of water. This means that the weight of a column of air reaching from the earth's surface to the limits of the atmosphere and having a cross section of one square inch weighs 15 pounds. The total mass of the atmosphere can be obtained by multiplying the weight of one column by the total area of the earth. In this way it is found that the mass of the earth's atmosphere is nearly 6,000,000,000,000,000 tons, or approximately one millionth the mass of the solid earth. The total mass of even the carbon dioxide of the earth's atmosphere is approximately 3,000,000,000,000 tons.

29. Determination of Height of Earth's Atmosphere from Observations of Meteors. — Meteors, or shooting stars as they are commonly called, are minute bodies, circulating in interplanetary space, which become visible only when they penetrate the earth's atmosphere and are made incandescent by the resistance which they encounter. The great heat developed is a consequence of their high velocities, which ordinarily are in the neighborhood of 25 miles per second.

Let m, Fig. 19, represent the path of a meteor before it encounters the atmosphere at A. Until it reaches A it is invisible, but at A it begins to glow and continues luminous until it is entirely burned up at B. Suppose it is observed from the two stations O_1 and O_2 which are at a known distance apart. The observations at O_1 give the angle AO_1O_2, and those at O_2 give the angle AO_2O_1. From these data the

other parts of the triangle can be computed (compare Art. 10). After the distance O_1A has been computed the perpendicular height of A from the surface of the earth can be computed by using the angle AO_1O_2. Similarly, the height of B above the surface of the earth can be determined.

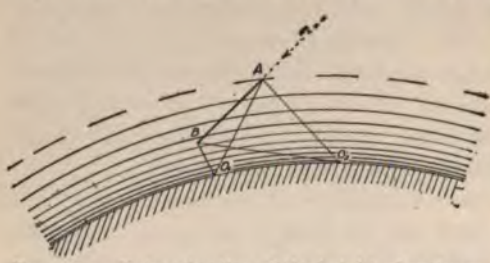


FIG. 19. — Determination of the height of meteors.

Observations of meteors from two stations show that they ordinarily become visible at a height of from 60 to 100 miles. Therefore, the atmosphere is sufficiently dense to a height of about 100 miles to offer sensible resistance to meteors. Meteors usually disappear by the time they have descended to within thirty or forty miles of the earth's surface.

30. Determination of Height of Earth's Atmosphere from Observations of Auroræ. — Auroræ are almost certainly electrical phenomena of the very rare upper atmosphere, though their nature is not yet very well understood. Their altitude can be computed from simultaneous observations made at different stations. The method is the same as that in obtaining the height of a meteor.

The southern ends of auroral streamers are usually more than 100 miles in height, and they are sometimes found at an altitude of 500 or 600 miles. Their northern ends are much lower. This means that the density required to make meteors incandescent is considerably greater than that which is sufficient for auroral phenomena.

31. Determination of Height of Earth's Atmosphere from the Duration of Twilight. — Often after sunset, even to the east of the observer, high clouds are brilliantly illuminated by the rays of the sun which still fall on them. The higher

the clouds are, the longer they are illuminated. Similarly, the sun shines on the upper atmosphere for a considerable time after it has set or before it rises, and gives the twilight. The duration of twilight depends upon the height of the atmosphere. While it is difficult to determine the instant at which the twilight ceases to be visible, observations show that under favorable weather conditions it does not disappear until the sun is 18 degrees below the horizon.

In order to see how the height of the atmosphere can be determined from the duration of the twilight, consider Fig. 20. The sun's rays come in from the left in lines that are sensibly parallel. The observer at O can see the illuminated atmosphere at P; but if the atmosphere were much shallower, it would not be visible to him. The region P is midway between O and the sunset point. Since O is 18 degrees from the sunset point, it is possible to compute the height of the plane of the horizon at P above the surface of the earth. It is found that 18 degrees corresponds to an altitude of 50 miles. That is, the atmosphere extends to a height of 50 miles above the earth's surface in quantities sufficient to produce twilight.

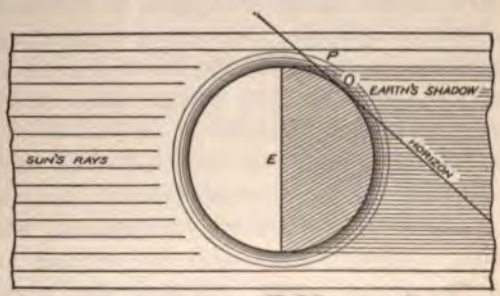


FIG. 20. — Determination of the height of the atmosphere from the duration of twilight.

The results obtained by the various methods for determining the height of the atmosphere disagree because its density decreases with altitude, as is found by ascending in balloons, and different densities are required to produce the different phenomena. It will convey the correct idea for most applications to state that the atmosphere does not extend in appreciable quantities beyond 100 miles above the earth's sur-

face. At this altitude its density is about one four hundred-millionth of that at the surface. When the whole earth is considered it is found that the atmosphere forms a relatively thin layer. If the earth is represented by a globe 8 inches in diameter, the thickness of the atmosphere on the same scale is only about one tenth of an inch.

32. The Kinetic Theory of Gases. — It has been stated that every known substance on the earth is composed of about 90 fundamental elements. A chemical combination of atoms is called a molecule. A molecule of oxygen consists of two atoms of oxygen, a molecule of water of two atoms of hydrogen and one of oxygen, and similarly for all substances. Some molecules contain only a few atoms and others a great many; for example, a molecule of cane sugar is composed of 12 atoms of carbon, 22 of hydrogen, and 11 of oxygen. As a rule the compounds developed in connection with the life processes contain many atoms.

The molecules are all very minute, though their dimensions doubtless vary with the number and kind of atoms they contain. Lord Kelvin devised a number of methods of determining their size, or at least the distances between their centers. In water, for example, there are in round numbers 300,000,000 in a line of them one inch long, or the cube of this number in a cubic inch.

In solids the molecules are constrained to keep essentially the same relations to one another, though they are capable of making complicated small vibrations. In liquids the molecules continually suffer restraints from neighboring molecules, but their relative positions are not fixed and they move around among one another, though not with perfect freedom. In gases the molecules are perfectly free from one another except when they collide. They move with great speed and collide with extraordinary frequency; but, in spite of the frequency of the collisions, the time during which they are influenced by their neighbors is very much greater than that in which they are in effective contact.

The pressure exerted by a gas is due to the impact of its molecules on the walls of the retaining vessel. To make the ideas definite, consider a cubic foot of atmosphere at sea-level pressure. Its weight is about one and one fourth ounces, but it exerts a pressure of 15 pounds on each square inch of each of its six surfaces, or a total pressure on the surface of the cube of more than six tons. This implies that the molecules move with enormous speed. They do not all move with the same speed, but some travel slowly while others go much faster than the average. Theoretically, at least, in every gas there are molecules moving with every velocity, however great, but the number of those having any given velocity diminishes rapidly as its difference from the average velocity increases. The average velocity of molecules in common air at ordinary temperature and pressure is more than 1600 feet per second, and on the average each molecule has 5,000,000,000 collisions per second. Therefore the average distance traveled between collisions is only about $\frac{1}{250000}$ of an inch.

From the kinetic theory of gases it is possible to determine how fast the density of the air diminishes with increase of altitude. It is found that about one half of the earth's atmosphere is within the first 3.5 miles of its surface, that one half of the remainder is contained in the next 3.5 miles, and so on until it is so rare that the kinetic theory no longer applies without sensible modifications.

33. The Escape of Atmospheres. — Suppose a body is projected upward from the surface of the earth. The height to which it rises depends upon the speed with which it is started. The greater the initial speed, the higher it will rise, and there is a certain definite initial velocity for which, neglecting the resistance of the air, it will leave the earth and never return. This is the velocity of escape, and for the earth it is a little less than 7 miles per second.

The molecules in the earth's atmosphere may be considered as projectiles which dart in every direction. It has

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collision. The earth is so
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molecule, that probably an
the number of mole-
gained. The situation is
water placed in a sealed
the air above it becomes

so nearly saturated that the vessel acquires as many molecules of water vapor by collisions as it loses by evaporation.

The doctrine of the escape of atmospheres implies that bodies of small mass will have limited and perhaps inappreciable atmospheres, and that those of large mass will have extensive atmospheres. The implications of the theory are exactly verified in experience. For example, the moon, with a mass $\frac{1}{70}$ that of the earth and a velocity of escape of about 1.5 miles per second, has no sensible atmosphere. On the other hand, Jupiter, with a mass 318 times that of the earth and a velocity of escape of 37 miles per second, has an enormous atmosphere. These examples are typical of the facts furnished by all known celestial bodies.

34. Effects of the Atmosphere on Climate. — Aside from the heat received from the sun, the most important factor affecting the earth's climate is its atmosphere. It tends to equalize the temperature in three important ways. (*a*) It makes the temperature at any one place more uniform than it would otherwise be, and (*b*) it reduces to a large extent the variations in temperature in different latitudes that would otherwise exist. And (*c*) it distributes water over the surface of the earth.

(*a*) Consider the day side of the earth. The rays of the sun are partly absorbed by the atmosphere and the heating of the earth's surface is thereby reduced. The amount absorbed at sea level is possibly as much as 40 per cent. Every one is familiar with the fact that on a mountain, above a part of the atmosphere, sunlight is more intense than it is at lower levels. But at night the effects are reversed. The heat that the atmosphere has absorbed in the daytime is radiated in every direction, and hence some of it strikes the earth and warms it. Besides this, at night the earth radiates the heat it has received in the daytime. The atmosphere above reflects some of the radiated heat directly back to the earth. Another portion of it is absorbed and radiated in every direction, and consequently in part back

to the earth. In short, the atmosphere acts as a sort of blanket, keeping out part of the heat in the daytime, and helping to retain at night that which has been received. Its action is analogous to that of a glass with which the gardener covers his hotbed. The results are that the variations in temperature between night and day are reduced, and the average temperature is raised.

(*b*) The unequal heating of the earth's atmosphere in various latitudes is the primary cause of the winds. The warmer air moves toward the cooler regions, and the cold air of the higher latitudes returns toward the equator. The trade winds are examples of these movements. Their importance will be understood when it is remembered that wind velocities of 15 or 20 miles an hour are not uncommon, and that there is about 15 pounds of air above every square inch of the earth's surface.

One of the effects of the winds is the production of the ocean currents which are often said to be dominant factors in modifying climate, but which are, as a matter of fact, relatively unimportant consequences of the air currents. A south wind will often in the course of a few hours raise the temperature of the air over thousands of square miles of territory by 20 degrees, or even more. In order to raise the temperature of the atmosphere at constant pressure, over one square mile through 20 degrees by the combustion of coal it would be necessary to burn ten thousand tons. This illustration serves to give some sort of mental image of the great influence of air currents on climatic conditions, and if it were not for them, it is probable that both the equatorial and polar regions would be uninhabitable by man.

35. Importance of the Constitution of the Atmosphere. — The blanketing effect of the atmosphere depends to a considerable extent on its constitution. Every one is familiar with the fact that the early autumn frosts occur only when the air is clear and has low humidity. The reason is that water vapor is less transparent to the earth's radiations than

are nitrogen and oxygen gas. On the other hand, there is not so much difference in their absorption of the rays that come from the sun. The reason is that the very hot sun's rays are largely of short wave length (Art. 211); that is, they are to a considerable extent in the blue end of the spectrum, while the radiation from the cooler earth is almost entirely composed of the much longer heat rays. Ordinary glass has the same property, for it transmits the sun's rays almost perfectly, while it is a pretty good screen for the rays emitted by a stove or radiator.

The water-vapor content of the atmosphere varies and cannot surpass a certain amount. But carbon dioxide has the same absorbing properties as water vapor, and in spite of the fact that it makes up only a very small part of the earth's atmosphere, Arrhenius believes that it has important climatic effects. He concluded that if the quantity of it in the air were doubled the climate would be appreciably warmer, and that if half of it were removed the average temperature of the earth would fall. Chamberlin has shown that there are reasons for believing that the amount of carbon dioxide has varied in long oscillations, and he suggested that this may be the explanation of the ice ages, with intervening warm epochs, which the middle latitudes have experienced.

If the effect of carbon dioxide on the climate has been correctly estimated, its production by the recent enormous consumption of coal raises the interesting question whether man at last is not in this way seriously interfering with the cosmic processes. At the present time about 1,000,000,000 tons of coal are mined and burned annually. In order to burn 12 pounds of coal 32 pounds of oxygen are required, and the result of the combustion is $12 + 32 = 44$ pounds of carbon dioxide. Consequently, by the combustion of coal there is now annually produced by man about 3,670,000,000 tons of carbon dioxide. On referring to the total amount of carbon dioxide now in the air (Art. 28), it

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... gen is given back to the air.

... Refraction of Light by the ...sphere. — When light passes
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... ent toward the perpendic-
... to the surface between the
... media, and in general the
... the difference in the densi-
... of the two media, the greater
... refraction. Thus, in Fig. 21,
... the surface of the denser medium
... tion AB toward the perpendicular
... takes the direction AC.

Now consider a ray of light striking the earth's atmosphere obliquely. The density of the air increases from its outer borders to the surface of the earth. Consequently, a ray of light is bent more and more as it proceeds down through the air. Let l, Fig. 22, represent a ray of light coming from a star S to an observer at O. The star is really in the direction OS'', but it appears to be in the direction OS' from which the light comes when it strikes the observer's eye. The angle between OS'' and OS' is the angle of refraction. It is zero for a star at the zenith and increases to a little over one-half of a degree for one at the horizon. For this reason a

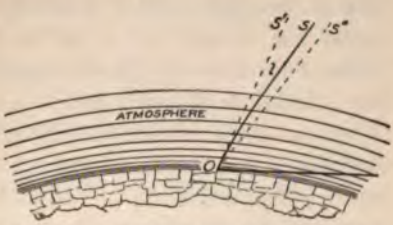


FIG. 22. — Refraction of light by the earth's atmosphere.



FIG. 23. — The sun is apparently flattened by refraction when it is on the horizon.

celestial body apparently rises before it is actually above the horizon, and is visible until after it has really set. If the sun or moon is on the horizon, its bottom part is apparently raised more than its top part by refraction, so that it seems to be flattened in the vertical direction, as is shown in Fig. 23.

38. The Twinkling of the Stars. — The atmosphere is not of uniform density from its highest regions to the surface of the earth, but it is always disturbed by waves which cause the density at a given point to vary continually. These variations in density cause constant small changes in the refraction of light, and consequently alterations in the direction from which the light appears to come. When the source is a point of light, as a star, it twinkles or scintillates. The twinkling of the stars is particularly noticeable in winter time on nights when the air is cold and unsteady. The variation in refraction is different for different colors, and consequently when a star twinkles it flashes sometimes red and sometimes green and at other times red or yellow. Objects that have disks, even though they are too small to be discerned with the unaided eye, appear much steadier than stars because the irregular refractions from various parts seldom agree in direction, and consequently do not displace the whole object.

QUESTIONS

1. What is the weight of the air in a room 16 feet square and 10 feet high?
2. How many pounds of air pass per minute through a windmill 20 feet in diameter in a breeze of 20 miles per hour?
3. Compute the approximate total atmospheric pressure to which the earth is subject.
4. What is the density of the air, compared to its density at the surface of the earth, at heights of 50, 100, and 300 miles, the density being determined by the law given at the end of Art. 32? This gives an idea of the density required for the phenomena of twilight, of meteors, and of auroræ.
5. Draw a diagram showing the earth and its atmosphere to scale.
6. The earth's mass is slowly growing by the acquisition of meteors. If there is nothing to offset this growth, will its atmosphere continue to increase or to decrease in amount?
7. If the earth's atmosphere increases or decreases, as the case may be, what will be the effect on the mean temperature, the daily range at any place, and the range over the earth's whole surface?
8. If the earth's surface were devoid of water, what would be the effect on the mean temperature, the daily range at any place, and the range over the whole surface?

CHAPTER III

THE MOTIONS OF THE EARTH

I. The Rotation of the Earth

39. The Relative Rotation of the Earth. — The most casual observer of the heavens has noticed that not only the sun and moon, but also the stars, rise in the east, pass across the sky, and set in the west. At least this is true of those stars which cross the meridian south of the zenith. Figure 24 is a photograph of Orion in which the telescope was kept fixed while the stars passed in front of it, and the horizontal streaks are the images traced out by the stars on the photographic plate.



Fig. 24. — Star trails of brighter stars in Orion (Barnard).

The stars in the northern heavens describe circles around the north pole of the sky as a center. Two hours of observation of the position of the Big Dipper will show the character of the motion very clearly. Figure 25 shows circumpolar star trails secured by pointing a fixed telescope toward the pole star and giving an exposure of a little over an hour. The conspicuous streak a little below and to the left of the center is the trail of the pole star, which therefore is not exactly at the pole of the heavens. A comparison of this picture with

38. The Twinkling of the Stars. — T
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face of the earth, but it is always distur
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with the unaided eye, appear much stea
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IV. QUESTIONS

1. What is the weight of the air in a
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3. Compute the approximate total atm
a person is subject.

4. What is the density of the air, comp
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and of auroræ.

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have a tendency to increase or to decrease

7. If the earth's atmosphere increase
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8. If the earth's surface were devoid o
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Newton called them *axioms* although they
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ewton gave them, are:

the northern sky will show that most of the stars who trails are seen are quite invisible to the unaided eye.

Since all the heavenly bodies rise in the east (except tho so near the pole that they simply go around it), travel acro the sky, and s in the west, reappear again the east, it fo lows that eith they go arou the earth fro east to west, the earth tur from west east. So far the simple m tions of the su moon, and sta are concern both hypothe are in perf harmony wi the observatio and it is not p sible to de which of them is correct without additional data. All apparent motions prove is that there is a relative mo of the earth with respect to the heavenly bodies.



FIG. 25. — Circumpolar star trails (Ritchey).

It is often supposed that the ancients were unscien if not stupid, because they believed that the earth was and that the sky went around it, but it has been seen so far as their data bore on the question one theory w good as the other. In fact, not all of them thought the earth was fixed. The earliest philosopher who is k to have believed in the rotation of the earth was Phil a Pythagorean, who lived in the fifth century B.C.

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[redacted] to be used fundamentally in [redacted] the question of their [redacted] are applied to the motions [redacted] becomes orderly. Be- [redacted] millions of times in [redacted] the earth and they have been tested [redacted] has been found to indicate they [redacted] the actual motions of material bodies. [redacted] represented by such an enormous mass [redacted] are among the most trustworthy con- [redacted].

[redacted] Earth Proved by Its Shape. — The [redacted] be determined without knowing whether [redacted] simple measurements of arcs (Art. 12) [redacted] obtain.

[redacted] it follows from the laws of motion [redacted] that the earth would be spherical [redacted]. Since it is not spherical, it must be [redacted] it follows from the laws of motion [redacted] it will be bulged at the equator. Hence [redacted] the earth proves that it rotates and deter- [redacted] of its axis, but does not determine in [redacted] it turns.

[redacted] of the Earth Proved by the Eastward Devi- [redacted] Bodies. — Let *OP*, Fig. 27, represent a

tower from whose top a ball is dropped. Suppose that while the ball is falling to the foot of the tower the earth rotates through the angle QEQ'. The top of the tower is carried from P to P', and its foot from O to O'. The distance PP' is somewhat greater than the distance OO'. Now consider the falling body. It tends to move in the direction PP' in accordance with the first law of motion because, at the time it is dropped, it is carried in this direction by the rotation of the earth. Moreover, PP' is the distance through which it would be carried if it were not dropped. But the earth's attraction causes it to descend, and the force acts at *right angles* to the line PP'. Therefore, by the second law of motion, the attraction of the earth does not have any influence on the motion in the direction PP'. Consequently, while it is descending it moves in a horizontal direction a distance equal to PP' and strikes the surface at O'' to the east of the foot of the tower O'. The eastward deviation is the distance $O'O''$. The small diagram at the right shows the tower and the path of the falling body on a larger scale.

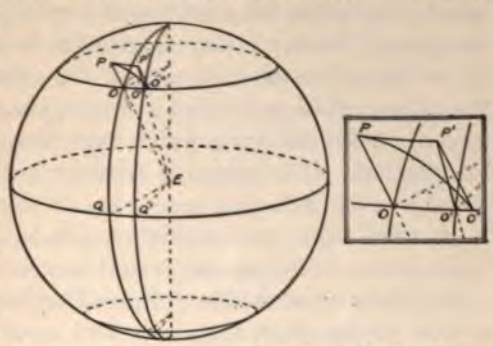


FIG. 27. — The eastward deviation of falling bodies proves the eastward rotation of the earth.

The foregoing reasoning has been made on the assumption that the earth rotates to the eastward. The question arises whether the conclusions are in harmony with experience. The experiment for determining the deviation of falling bodies is complicated by air currents and the resistance of the air. Furthermore, the eastward deviation is very small, being only 1.2 inches for a drop of 500 feet in latitude 40°. In

reason is, of course, that the weak man does not g
strong one an opportunity to use his full strength.
strong man is heavier than the weak one and pulls
he will move the latter while he remains in his track
seems to contradict the statement of the law in
the acceleration; but the contradiction disappears
is remembered that the men are subject not only to
they exert on each other, but also to their friction
earth. If they were in canoes in open water, the
both move, and, if the weights of the canoes were
their motions would be in harmony with the third

Since the laws of motion are to be used fundame
considering the motion of the earth, the question
truth at once arises. When they are applied to the
of the heavenly bodies, everything becomes orde
sides this, they have been illustrated millions of
ordinary experience on the earth and they have be
in laboratories, but nothing has been found to indi
are not in harmony with the actual motions of materi
In fact, they are now supported by such an enorm
of experience that they are among the most trustwo
clusions men have reached.

41. Rotation of the Earth Proved by Its Shap shape of the earth can be determined without knowin or not it rotates. The simple measurements of arcs prove that the earth is oblate.

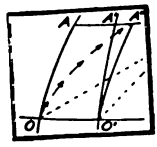
It can be shown that it follows from the laws and the law of gravitation that the earth would b if it were not rotating. Since it is not spherical, rotating. Moreover, it follows from the laws that if it is rotating it will be bulged at the equato the oblateness of the earth proves that it rotates mines the position of its axis, but does not det which direction it turns.

42. Rotation of the Earth Proved by the Eastw ation of Falling Bodies. — Let *OP*, Fig. 27, r

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spite of these difficulties, the experiment for moder
proves that the earth rotates to the eastward. Fat
of Rome, has devised an apparatus, having ana
Atwood's machine in physics, which avoids most
turbances to which a freely falling body is sub
largest free fall so far tried was in a vertical mine
Houghton, Mich., more than 4000 feet deep.
of the fact that the diameter of the mine shaft
times the deviation for that distance, the experim
failed because the balls which were dropped nev
the bottom. It is probable that when they had
enough to acquire high speed the air packed up
them until they were suddenly deflected far en
their course to hit the walls and become imbed

43. Rotation of the Earth Proved by Foucault's — One of the most ingenious and convincing for pr rotatio earth in 18 Frenc Fouca pends fact t ing to motio swing lum stantl the sa

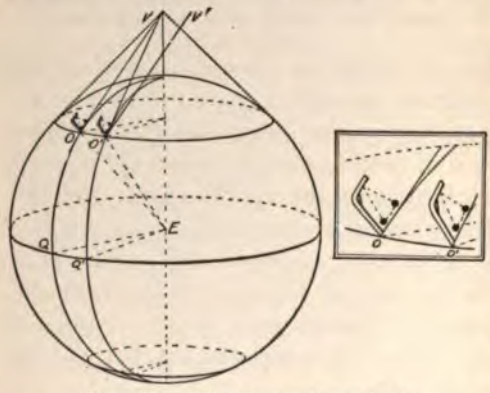
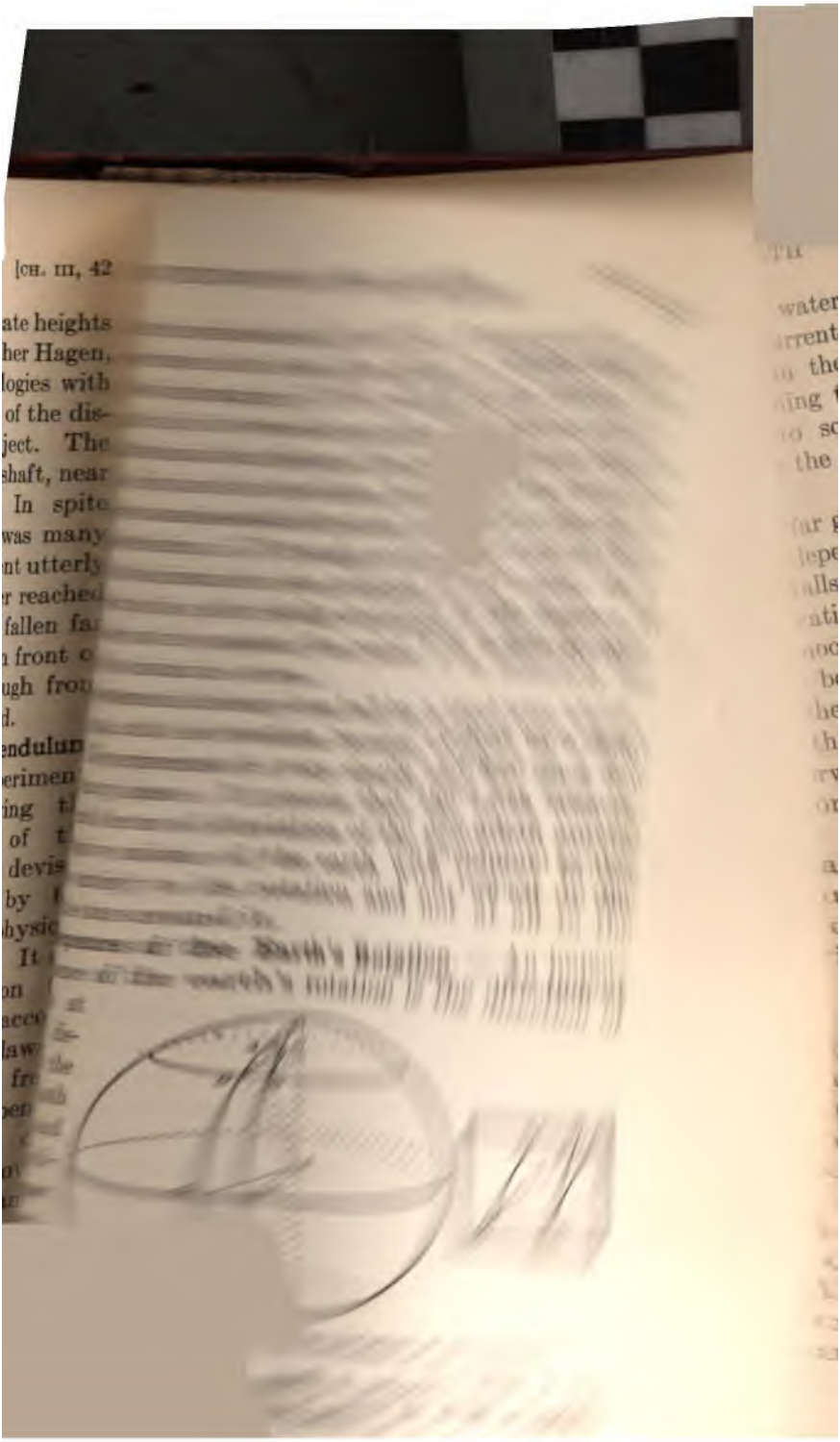


FIG. 28. — The Foucault pendulum.

Suppose a pendulum suspended at O, Fig. 2 swinging in the meridian OQ. Let OV be the t drawn in the plane of the meridian. After a cer the meridian OQ will have rotated to the po The line $O'V'$ is drawn parallel to the line O quently the pendulum will be swinging in the p

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interval of time. Suppose that in this interval of time the meridian OQ rotates to the position $O'Q'$. Hence the mass of air under consideration actually had the velocities OA and OO' when it started from O, the former with respect to the surface of the earth and the latter because of the rotation of the earth. By the laws of motion these motions, being at right angles to each other, are mutually independent, and the air will move over both distances during the interval of time and arrive at the point A'', which is east of A'. Consequently, the mass of air that started straight northward with respect to the surface of the earth along the meridian OA will have deviated eastward by the amount $A'A''$.

The deviation for northward motion in the northern hemisphere is toward the east; for southward motion, it is toward the west. In both cases it is toward the right. For similar reasons, in the southern hemisphere the deviation is toward the left.

The deviations in the directions of air currents are evidently greater the higher the latitude, because near the poles a given distance along the earth's surface corresponds to an almost equal change in the distance from the axis of rotation, while at the equator there is no change in the distance from the earth's axis. It might be supposed that in middle latitudes a moderate northward or southward displacement of the air would cause no appreciable change in its direction of motion. But a point on the equator moves eastward at the rate of over 1000 miles an hour, at latitude 60 degrees the eastward velocity is half as great, and at the pole it is zero. If it were not for friction with the earth's surface, a mass of air moving from latitude 40 degrees to latitude 45 degrees, a distance less than 350 miles, would acquire an eastward velocity with respect to the surface of the earth of over 40 miles an hour. The prevailing winds of the northern hemisphere in middle latitudes are to the northeast, and the eastward component has been found to be strong for the very high currents.

Obviously the same principles apply to water currents and to air currents. Consequently water currents, such as rivers, tend to deviate toward the right in the northern hemisphere. It has been found by examining the Mississippi and Yukon rivers that the former to some extent, and the latter to a much greater extent, on the whole scour their right-hand banks.

All the proofs of the earth's rotation so far given depend upon the laws of motion. There is one independent reason for believing the earth rotates, though it falls a little short of proof. It has been found by observations involving only geometrical principles that the sun, moon, and planets are comparable to the earth in size, some being larger and others smaller. Direct observations with the telescope show that a number of these bodies rotate on their axes, the remainder being either very remote or otherwise unfavorably situated for observation. The conclusion by analogy is that the earth also rotates.

45. The Uniformity of the Earth's Rotation. — It follows from the laws of motion, and in particular from the first law, that if the earth were subject to no external forces and were invariable in size, shape, and distribution of mass, it would rotate on its axis with absolute uniformity. Since the earth is a fundamental means of measuring time its rotation cannot be tested by clocks. Its rotation might be compared with other celestial phenomena, but then the question of their uniformity would arise. The only recourse is to make an examination of the possible forces and changes in the earth which are capable of altering the rate of its rotation.

The earth is subject to the attractions of the sun, moon, and planets. But these attractions do not change its rate of rotation because the forces pulling on opposite sides balance, just as the earth's attraction for a rotating wheel whose plane is vertical neither retards nor accelerates its motion.

The earth is struck by millions of small meteors daily coming in from all sides. They virtually act as a resisting medium and slightly retard its rotation, just as a top spinning in the air is retarded by the molecules impinging on it. But the mass of the earth is so large and the meteors are so small that, at their present rate of infall, the length of the day cannot be changed by this cause so much as a second in 100,000,000 years.

The moon and the sun generate tides in the water around the earth and the waves beat in upon the shores and are gradually destroyed by friction. The energy of the waves is transformed into heat. This means that something else has lost energy, and a mathematical treatment of the subject shows that the earth has suffered the loss. Consequently its rotation is diminished. But as great and irresistible as the tides may be, their energies are insignificant compared to that of the rotating earth, and according to the work of MacMillan the day is not increasing in length from this cause more than one second in 500,000 years.

Before discussing the effects of a change in the size of the earth or in the distribution of its mass, it is necessary to explain a very important property of the motion of rotating bodies. It can be shown from the laws of motion that if a body is not subject to any exterior forces, its total quantity of rotation always remains the same no matter what changes may take place in the body itself. The quantity of rotation of a body, or *moment of momentum*, as it is technically called in mechanics, is the sum of the rotations of all its parts. The rotation of a single part, or particle, is the product of its mass, its distance from the axis of rotation passing through the center of gravity of the body, and the speed with which it is moving at right angles to the line joining it to the axis of rotation. It can be shown that in the case of a body rotating as a solid, the quantity of rotation is proportional to the product of the square of the radius and the angular velocity of rotation, the angular velocity of

rotation being the angle through which the body turns in a unit of time.

Now apply this principle of the conservation of the moment of momentum to the earth. If it should lose heat and shrink so that its radius were diminished in length, then the angular velocity of rotation would increase, for the product of the square of the radius and the rate of rotation must be constant. On the other hand, if the radio-active substances in the earth should cause its temperature to rise and its radius to expand, then the rate of rotation would decrease. Neither of these causes can make a sensible change in the rotation in 1,000,000 years. Similarly, if a river rising in low latitudes should carry sediment to higher latitudes and deposit it nearer the earth's axis, then the rate of rotation of the earth would be increased. While such factors are theoretically effective in producing changes in the rotation of the earth, from a practical point of view they are altogether negligible.

It follows from this discussion that there are some influences tending to decrease the rate of the earth's rotation, and others tending to increase it, but that they are all so small as to have altogether inappreciable effects even in a period as long as 100,000 years.

46. The Variation of Latitude. — It was mentioned in connection with the discussion of the rigidity of the earth (Arts. 25, 26), that its axis of rotation is not exactly fixed. This does not mean that the direction of the axis changes, but that the position of the earth itself changes so that its axis of rotation continually pierces different parts of its surface. That is, the poles of the earth are not fixed points on its surface. Since the earth's equator is 90 degrees from its poles, the position of the equator also continually changes. Therefore the latitude of any fixed point on the surface of the earth undergoes continual variation. The fact was discovered by very accurate determinations of latitude, and for this reason is known as the variation of latitude.

The pole wanders from its mean
30 feet, corresponding to a change
second of arc. This is such a small
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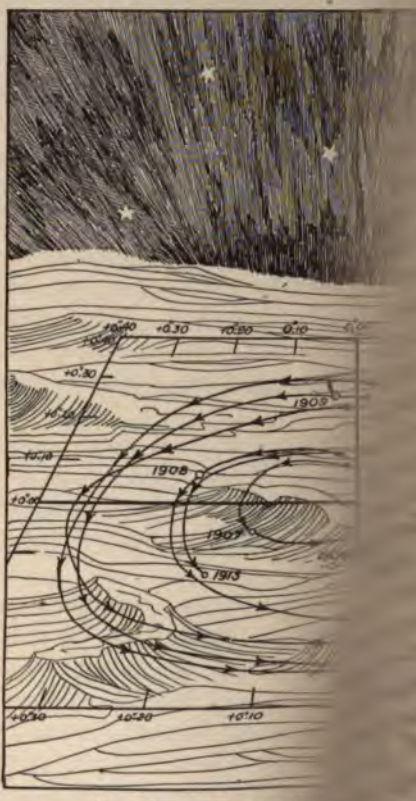
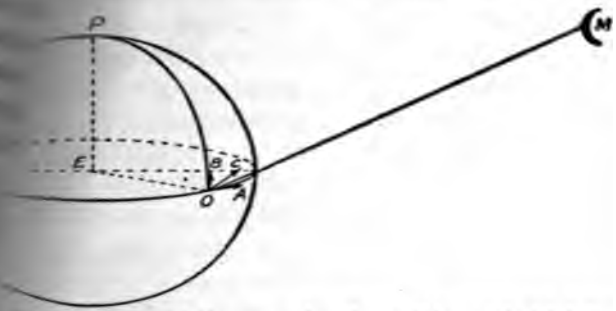


FIG. 30. — The positi

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Küstner about 1885.

In 1891 Chandler too
the observations how th
tion in its position is v

the resolution of forces (the inverse of the forces law) the force along OM can be resolved into two others, one along OE and the other along the perpendicular to OE. The former of these two forces acts on the rotation; the latter tends to move



The attraction of the moon for the earth's equatorial bulge causes the precession of the equinoxes.

particle in the direction OB, and this tendency, combined with the velocity OA, causes it to move in the direction OC (the change is greatly exaggerated). Therefore the direction of motion of O is changed; that is, the plane of the equator is changed.

The moon, however, attracts every particle in the equatorial bulge of the earth, and its effects vary with the position of the particles. It can be shown by a mathematical discussion that cannot be taken up here that the combined effect on the entire bulge is to change the plane of the equator. It is evident from Fig. 31 that the effect vanishes when the moon is in the plane of the earth's equator. Therefore it is natural to take the plane of the moon's orbit as a plane of reference. These two planes intersect in a certain line whose position changes as the plane of the earth's equator is shifted. **The plane** of the earth's equator shifts in such a way that **the angle** between it and the plane of the moon's orbit is **constant,** while the line of intersection of the two planes ro-

pendulum which natu
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be particularly important if it were not for the further fact that the plane of the moon's orbit has a sort of precession with respect to the ecliptic, completing a cycle in 18.6 years. This introduces a variation in the character of the precession which is periodic with the same period of 18.6 years. This variation in the precession, which at its maximum amounts to 9.2 seconds of arc, is called the *nutation*. It was discovered by the great English astronomer Bradley from observations made during the period from 1727 to 1747. The cause of it was first explained by D'Alembert, a famous French mathematician.

V. QUESTIONS

1. Which of the proofs of the rotation of the earth depend upon the laws of motion?
2. Give three practical illustrations (one a train moving around a curve) of the first law of motion.
3. Give three illustrations of the second law of motion.
4. Why is the kick in a heavy gun, for a given charge, less than in a light gun?
5. If a man fixed on the shore pulls a boat by a rope, do the interactions not violate the third law of motion?
6. For a body falling from a given height, in what latitude will the eastward deviation be the greatest?
7. For what latitude will the rotation of the Foucault pendulum be most rapid, and where would the experiment fail entirely?
8. In what latitude will the easterly (or westerly) deviation of wind or water currents be most pronounced?
9. Is it easier to stop a large or small wheel of the same mass rotating at the same rate?
10. If a wheel rotating without friction should diminish in size, would its rate of rotation be affected?
11. Are boundaries that are defined by latitudes affected by the wabbling of the earth's axis? By the precession of the equinoxes?
12. Would the precession be faster or slower if the earth were more oblate? If the moon were nearer? If the earth were denser?

tates in the direction opposite to that [illegible] turns on its axis.

The plane in which the sun moves is [illegible]ect to the *the ecliptic*, and the moon is always ne[illegible]s that the the moment neglect its departure fro[illegible] it is not ecliptic. Then the moon, and the sun [illegible]ward motion line of the intersection of the plane o[illegible] which every and the plane of the ecliptic, called the [illegible] so familiar to rotate in the direction opposite to [illegible] stars cannot the earth. This is the precession o[illegible]pic aid, and, fifths of which is due to the moon an[illegible] that it ap- due to the sun. Since the axis of the [illegible] use of optical to the plane of its equator, the point [illegible] ancient times. the axis is directed describes a circle [illegible]

The mass of the earth is so great [illegible] relatively so small, and the forces d[illegible] are so feeble that the precession is v[illegible] to 50.2 seconds of arc per year, fr[illegible] the line of the equinoxes will make [illegible] after more than 25,800 years have [illegible]

The precession of the equinoxe[illegible] parchus about 120 B.C. from a c[illegible] tions with those made by earlier [illegible] of it was not known until it wa[illegible] 1686, in his Principia. The the[illegible] the precession are in perfect har[illegible] and the weight of this stateme[illegible]



[illegible]round the earth explains [illegible]th respect to the stars.

[illegible]s are seen directly south it is remembered that the calcu[illegible]ght. The sun is therefore of the earth, its density, the d[illegible] equivalent, the stars in laws of motion, the rate of rota[illegible] sun. A month later at 8 ness, the distances to the moo[illegible]ars will be found to be 30° tions with respect to the earth[illegible] that time in the evening the

The moon does not move [illegible]ian, the stars are 120° − 30° ecliptic, but deviates from [illegible]; that is, during a month the sun consequently the precession [illegible]ward with respect to the stars. with respect to the ecliptic. [illegible]ther or not the sun's apparent

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shown that the hypothesis that it
l the earth satisfies all the data so far
E, Fig. 32, represents the earth,
S_1 the position of the sun at a certain
m the earth it will appear to be on the sky
at S_1'. Suppose that at the end of 25 days
ved forward in a path around the earth to
; it will then appear to be among the stars at
it will appear to have moved eastward among
perfect accordance with the observations of its
otion.

ow be shown that the same observations can be
mpletely by the hypothesis that the earth re-

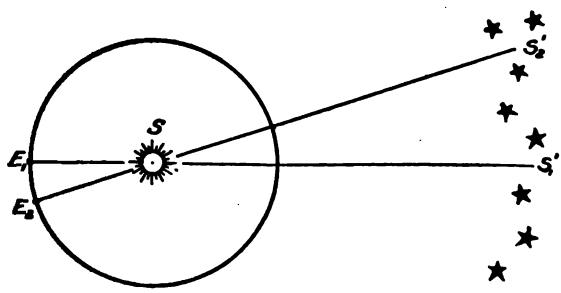


FIG. 33. — The hypothesis that the earth revolves around the sun explains the apparent eastward motion of the sun with respect to the stars.

volves around the sun. Let S, Fig. 33, represent the sun, assumed fixed, and suppose E_1 is the position of the earth at a certain time. The sun will appear to be among the stars at S_1'. Suppose that at the end of 25 days the earth has moved forward in a path around the sun to E_2; the sun will then appear to be among the stars at S_2'. That is, it will appear to have moved eastward among the stars in perfect accordance with the observations of its apparent motion. It is noted that the assumed actual motion of the earth is in the same direction as the sun's apparent motion; or, to explain

II. The Revolution of the Earth

48. Relative Motion of the Earth with Respect to the Sun. — The diurnal motion of the sun is so obvious that the most careless observer fully understands it. It is so well known that the sun has an apparent eastward motion among the stars analogous to that of the moon, which everyone has noticed. The reason that people are not familiar with the apparent motion of the sun is that the stars cannot be observed in its neighborhood without telescopes, and besides, it moves slowly. However, the fact that it apparently moves can be established without the use of instruments; indeed, it was known in very

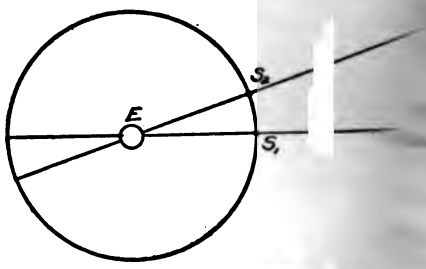


Fig. 32. — The hypothesis that the sun revolves around the earth explains the apparent eastward motion of the sun

Suppose on a given date certain star is on the meridian at 8 o'clock at night. Then at 4 o'clock it is 120° west of the star; or, what is the same thing, the sun in question are 120° east of the star. Hence at 4 o'clock at night the observed star is on the meridian. Since the sun is 120° west of the meridian, it is 90° east of the sun. Therefore the sun apparently has moved 30° eastward.

The question arises whether

the apparent motion of the sun by the motion of the earth, the earth must be supposed to move eastward in its orbit.

Since all the data satisfy two distinct and mutually contradictory hypotheses, new data must be employed in order to determine which of them is correct. The ancients had no facts by which they could disprove one of these hypotheses and establish the truth of the other.

49. Revolution of the Earth Proved from the Laws of Motion. — The first actual proof that the earth revolves around the sun was based on the laws of motion in 1686, though the fact was generally believed by astronomers somewhat earlier (Art. 62). It must be confessed at once, however, that the statement requires a slight correction because the sun and earth actually revolve around the center of gravity of the two bodies, which is very near the center of the sun because of the sun's relatively enormous mass.

It can be shown by measurements that have no connection with the motion of the sun or earth that the volume of the sun is more than a million times that of the earth. Hence, unless it is extraordinarily rare, its mass is much greater than that of the earth. In view of the fact that it is opaque, the only sensible conclusion is that it has an appreciable density. Hence, in the motion of the earth and sun around their common center of gravity, the sun is nearly fixed while the earth moves in an enormous orbit.

50. Revolution of the Earth Proved by the Aberration of Light. — The second proof that the earth revolves was made in 1728 when Bradley discovered what is known as the *aberration of light.* This proof has the advantage of depending neither on an assumption regarding the density of the sun nor on the laws of motion.

Suppose rain falls vertically and that one stands still in it; then it appears to him that it comes straight down. Suppose he walks rapidly through it; then it appears to fall somewhat obliquely, striking him in the face. Suppose he rides through it rapidly; then it appears to descend more obliquely.

In order to get at the matter qualitatively suppose T_1, Fig. 34, is a tube at rest which is so placed in such a position that drops of rain shall descend through it without striking the sides. Clearly it must be vertical. Suppose T_2 is a tube which is being carried to the right with moderate speed. It is evident that the tube must be tilted slightly in the direction of motion. Suppose the tube T_3 is being transported still more rapidly: it must be given a greater deviation from the vertical. The distance A_3C_3 is the distance the tube moves while the drop descends its length. Hence A_3C_3 is to B_3C_3 as the velocity of the tube is to the velocity of the drops. From the given velocity of the rain and the velocity of the tube at right angles to the direction of the rain, the angle of the deviation from the vertical, namely $A_3B_3C_3$, can be computed.

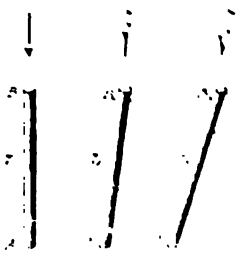


FIG. 34. Explains the aberration of light

Now suppose light from a distant star is considered instead of falling rain, and let the tube represent a telescope. All the relations will be qualitatively as in the preceding case because the velocity of light is not infinite. In fact it has been found by experiments on the earth, which in no way depend upon astronomical observations or theory, that light travels in a vacuum at the rate of 186,330 miles per second. Hence, if the earth moves, stars should appear displaced in the direction of its motion, the amount of the displacement depending upon the velocity of the earth and the velocity of light. Bradley observed such displacements, at one time of the year in one direction and six months later, when the earth was on the other side of its orbit, in the opposite direction. The maximum displacement of a star for this reason is 20.47 seconds of arc which, at the present time, is very easy to observe because measurements of position are now accurate to one hundredth of this amount.

Moreover, it is a quantity which does not depend on the brightness or the distance of the star, and it can be checked by observing as many stars as may be desired.

The aberration of light not only proves the revolution of the earth, but its amount enables the astronomer to compute the speed with which the earth moves. The result is accurate to within about one tenth of one per cent. Since the earth's period around the sun is known, this result gives the circumference of the earth's orbit, from which the distance from the earth to the sun can be computed. The distance of the sun as found in this way agrees very closely with that found by other methods.

There is, similarly, a small aberration due to the earth's rotation, which, for a point on the earth's equator, amounts at its maximum to 0.31 second of arc.

51. Revolution of the Earth Proved by the Parallax of the Stars. — The most direct method of testing whether or not the earth moves is to find whether the direction of a star is the same when observed at different times of the year. This was the first method tried, but for a long time it failed because the stars are exceedingly remote. Even with all the resources of modern instrumental equipment fewer than 100 stars are known which are so near that their



FIG. 38. — The parallax of A is the angle E_1AE_2.

differences in direction at different times of the year can be measured with any considerable accuracy. Yet the observations succeed in a considerable number of cases and really prove the motion of the earth by purely geometrical means.

The angular difference in direction of a star as seen from two points on the earth's orbit, which, in the direction perpendicular to the line to the star, are separated from each

other by the distance from the earth to the sun, is the *parallax* of the star. In Fig. 35 let S represent the sun, A a star, and E_1 and E_2 two positions of the earth such that the line E_1E_2 is perpendicular to SA and such that E_1E_2 equals E_1S. Let E_2B be parallel to E_1A. Then, by definition, the angle AE_2B is the parallax of A. This angle equals E_1AE_2. Therefore an alternative definition of the parallax of a star is that it is the angle subtended by the radius of the earth's orbit as seen from the star.

It is obvious that the parallax is smaller the more remote the star. The nearest known star, Alpha Centauri, in the southern heavens, has a parallax of only 0.75 second of arc, from which it can be shown that its distance is 275,000 times as great as that from the earth to the sun, or about 25,600,000,000,000 miles. Suppose a point of light is seen first with one eye and then with the other. If its distance from the observer is about 11 miles, then its difference in direction as seen with the two eyes is 0.75 second of arc, the parallax of Alpha Centauri. This gives an idea of the difficulties that must be overcome in order to measure the distance of even the nearest star, especially when it is recalled that the observations must be extended over several months. The first success with this method was obtained by Henderson about 1840.

52. Revolution of the Earth Proved by the Spectroscope. — The spectroscope is an instrument of modern invention which, among other things, enables the astronomer to determine whether he and the source of light he may be examining are relatively approaching toward, or receding from, each other. Moreover, it enables him to measure the speed of relative approach or recession irrespective of their distance apart. (Art. 226.)

Consider the observation of a star A, Fig. 36, in the plane of the earth's orbit when the earth is at E_1, and again when it is at E_2. In the first position the earth is moving toward the star at the rate of 18.5 miles per second, and in the second

position it is moving away from the star at the same rate. Since in the case of many stars the motion can be determined to within one tenth of a mile per second, the observational difficulties are not serious. If the star is not in the plane of the earth's orbit, a correction must be made in order to find what fraction of the earth's motion is toward or from the star. The method is independent of the distance of the star and can be applied to all stars which are bright enough except those whose directions from the sun are nearly perpendicular to the plane of the earth's orbit.

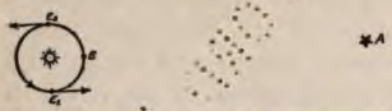


FIG. 36. — Motion of the earth toward and from a star.

Since 1890 the spectroscope has been so highly perfected that the spectroscopic proof of the earth's revolution has been made with thousands of stars. This method gives the earth's speed, and therefore the circumference of its orbit and its distance from the sun. It should be stated, however, that the motion of the earth was long ago so firmly established that it has not been considered necessary to use the spectroscope to give additional proof of it. Rather, it has been used to determine how the stars move individually (Art. 273) and how the sun moves with respect to them as a whole (Art. 274). In order to obtain the motion of a star with respect to the sun it is sufficient to observe it when the earth is at E, Fig. 36. Then correction for the earth's motion can be applied to the observations made when the earth is at E_1 or E_2.

53. Shape of the Earth's Orbit. — It has been tacitly assumed so far that the earth's orbit is a circle with the sun at the center. If this assumption were true, the apparent diameter of the sun would be the same all the year because the earth's distance from it would be constant. On the other hand, if the sun were not at the center of the circle, or if the orbit were not a circle, the apparent size of the sun

would vary with changes in the earth's distance from it. It is clear that the shape of the earth's orbit can easily be established by observation of the apparent diameter and position of the sun.

It is found from the changes in the apparent diameter of the sun that the earth's orbit is not exactly a circle. These changes and the apparent motion of the sun together prove that the earth moves around it in an elliptical orbit which differs only a little from a circle. An ellipse is a plane curve such that the sum of the distances from two fixed points in its interior, known as *foci*, to any point on its circumference is always the same.

In Fig. 37, E represents an ellipse and F and F' its two foci. The definition of an ellipse suggests a convenient way of drawing one. Two pins are put in drawing paper at a convenient distance apart and a loop of thread somewhat longer than twice this distance is placed over them. Then a pencil P is placed inside the thread and the curve is drawn, keeping the thread taut. The curve obtained in this way is obviously an ellipse because the length of the thread is constant, and this means that the sum of the distances from F and F' to the pencil P is the same for all points of the curve.

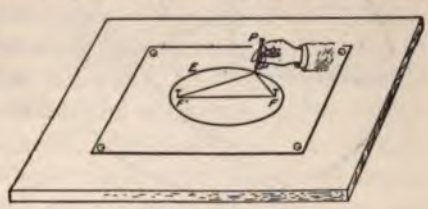


FIG. 37. — An ellipse.

54. Motion of the Earth in Its Orbit. — The earth moves in its orbit around the sun in such a way that the line drawn from the sun to the earth sweeps over, or describes, equal areas in equal intervals of time. Thus, in Fig. 38, if the three shaded areas are equal, the intervals of time required for the earth to move over the corresponding arcs of its orbit are also equal. This implies that the earth moves fastest when it is at P, the point nearest the sun, and slowest when

position it is [illegible] from the sun. The former is Since in the [illegible] and the latter the *aphelion point*. to within one [illegible] may be very nearly round or difficulties [illegible] of the elongation is defined

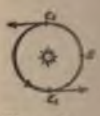


FIG. 36. — Mo[illegible]

[illegible] and [illegible]

[illegible]ent of the [illegible] [illegible]rth's orbit is very slight, being stars which [illegible] the distance CS, Fig. 38, in the from the sun [illegible] case of the earth's orbit is earth's orbit [illegible] about $\frac{1}{60}$ of CP. Hence, if the earth's orbit were drawn to scale, its elongation would be so slight that it would not be obvious by simple inspection.

Since 18[illegible] that the spe[illegible] made with [illegible] earth's speed [illegible] and its dis[illegible] that the mo[illegible] lished that [illegible] spectroscop[illegible] been used [illegible] (Art. 273) [illegible] whole (Ar[illegible] with respe[illegible] the earth [illegible] motion [illegible] earth is at [illegible]

The question arises as to what occupies the second focus of the elliptical orbit of the earth. The answer is that there is no body there; nor is it absolutely the earth's orbit is continually extent by the attractions of the

[illegible] the earth might revolve around the [illegible] were started with the right velocity.

53. Sha[illegible] to understand how it can revolve in an assumed [illegible] the sun at one of the foci. While the at the [illegible] fully explained without some rather fordiameter [illegible] considerations, it can, at least, be the earth's [illegible] little reflection. Suppose a body is at other hand [illegible] moving in the direction PT. If its speed is if the orbit [illegible] its centrifugal acceleration balances the

attraction of the sun, it will revolve around the sun in a circle.

But suppose the initial velocity is a little greater than that required for motion in a circular orbit. In this case the sun's attraction does not fully counterbalance the centrifugal acceleration, and the distance of the body from the sun increases. Consider the situation when the body has moved around in its orbit to the point Q. At this point the centrifugal acceleration is still greater than the attraction of the sun, and the distance of the body from the sun is increasing. It will be observed that the sun's attraction no longer acts at right angles to the direction of motion of the body, but that it tends to diminish its speed. It can be shown by a suitable mathematical discussion, which must be omitted here, that the diminution of the speed of the body more than offsets the decreasing attraction of the sun due to the increasing distance of the body, and that in elliptical orbits a time comes in which the attraction and the centrifugal acceleration balance. Suppose this takes place when the body is at R. Since its speed is still being diminished by the attraction of the sun from that point on, the attraction will more than counterbalance the centrifugal acceleration. Eventually at A the distance of the body from the sun will cease to increase. That is, it will again be moving at right angles to a line joining it to the sun; but its velocity will be so low that the sun will pull it inside of a circular orbit tangent at that point. It will then proceed back to the point P, its velocity increasing as it decreases in distance while going from A to P. The motion out from the sun and back again is analogous to that of a ball projected obliquely upward from the surface of the earth; its speed decreases to its highest point, and then increases again as it it descends.

55. Inclination of the Earth's Orbit. — The plane of the earth's orbit is called the *plane of the ecliptic*, and the line in which this plane intersects the sky is called the *ecliptic*. In

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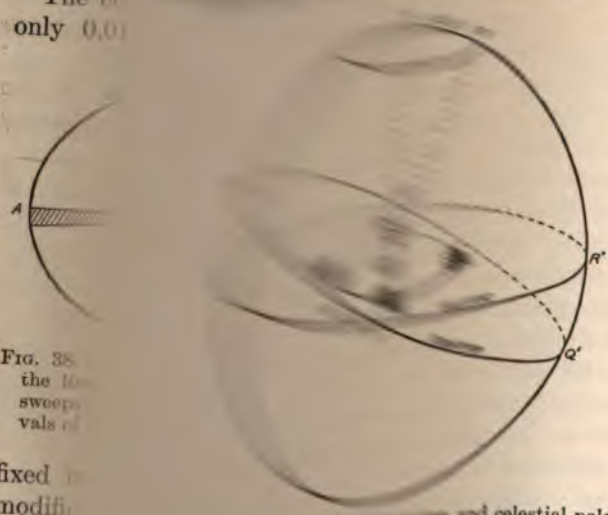


FIG. 38.
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and P is the pole of the
these lines is the same as the
degrees.
of the equinoxes (Art. 47).

The pole of the ecliptic remains fixed. As a consequence of the precession of the equinoxes the pole P describes a circle around it with a radius of 23.5 degrees, and the direction of the motion is opposite to that of the direction of the motion of the earth around the sun. Or, the points A and V, which are the equinoxes, continually move backward along the ecliptic in the direction opposite to that of the revolution of the earth.

56. Cause of the Seasons. — Let the upper part of the earth E, Fig. 39, represent its north pole. When the earth is at E_1 its north pole is turned away from the sun so that it is in continual darkness; but, on the other hand, the south pole is continually illuminated. At this time of the year the northern hemisphere has its winter and the southern hemisphere its summer. The conditions are reversed when the earth is at E_3. When the earth is at E_2 the plane of its equator passes through the sun, and it is the spring season in the northern hemisphere. Similarly, when the earth is at E_4 the equator also passes through the sun and it is autumn in the northern hemisphere.

Consider a point in a medium northern latitude when the earth is at E_1, and the same position again when the earth is at E_3. At E_1 the sun's rays, when it is on the meridian, strike the surface of the earth at the point in question more obliquely than when the earth is at E_3. Their intensity is, therefore, less in the former case than it is in the latter; for, in the former, the rays whose cross section is PQ, Fig. 40, are spread out over the distance AB, while in the latter they extend over the smaller distance $A'B$. This fact, and the variations in the number of hours of sunshine per day (Art. 58), cause the changes in the seasons.

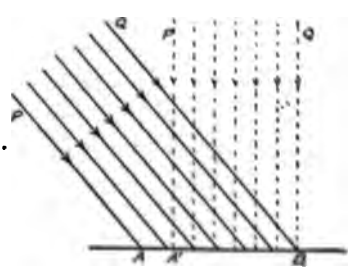
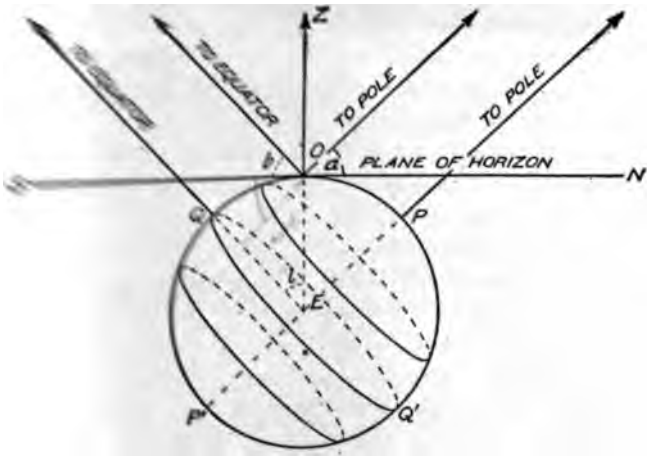


FIG. 40. — Effects of obliquity of sun's rays.

57. Relation of the Position of the Celestial Pole to the Latitude of the Observer. — In order to make clear the climatic effects of certain additional factors, consider the apparent position of the celestial pole as seen by an observer in any latitude. Since the pole is the place where the axis of the earth, extended, pierces the sky, it is obvious that, if an observer were at the north pole of the earth, the celestial equator would be on his horizon, the celestial pole would be at his zenith; while for an observer on the equator of the earth, the celestial equator would pass through his zenith, and the celestial poles would be on his horizon, north and south.

Consider an observer at O, in latitude l degrees north of the equator. $P'P$ points toward the



The altitude of the celestial pole equals the latitude of the observer.

celestial pole of the sky. Since the sky is extremely far away compared to the dimensions of the earth, the line from O to the celestial pole is essentially parallel to $P'P$. The angle between the plane of the horizon and the line to the pole is called the **altitude of the pole.** Since ON is perpendicular

to EO, and $P'P$ is perpendicular to EQ, it follows that a equals l, or *the altitude of the pole equals the latitude of the observer*.

Consider also the altitude of the equator where it crosses the meridian directly south of the observer. It is represented by b in the diagram. It easily follows that $b = 90° - l$, or the altitude of the equator where it crosses the meridian equals 90° minus the latitude of the observer.

58. The Diurnal Circles of the Sun. — It is evident from Fig. 39 that when the earth is in the position E_1, the sun is seen south of the celestial equator; when the earth is at E_2 or E_4, the sun appears to be on the celestial equator; and when the earth is at E_3, the sun is seen north of the celestial equator. If the equator is taken as the line of reference and the apparent motion of the sun is considered, its

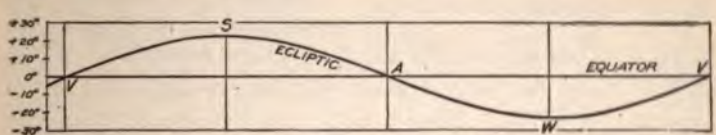


FIG. 42. — Relation of ecliptic and celestial equator.

position with respect to the equator is represented in Fig. 42. The sun appears to be at V when the earth is at E_2, Fig. 39. The point V is called the *vernal equinox*, and the sun has this position on or within one day of March 21. The sun is at S, called the *summer solstice*, when the earth is at E_3, Fig. 39, and it is in this position about June 21. The sun is at A, called the *autumnal equinox*, when the earth is at E_4, and it has this position about September 23. Finally, the sun is at W, which is called the *winter solstice*, when the earth is at E_1. The angle between the ecliptic and the equator at V and A is 23°.5; and the perpendicular distance between the equator and the ecliptic at S and W is 23°.5. From these relations and those given in Art. 57 the diurnal paths of the sun can readily be constructed.

57. Relation of the Position of the Celesti Latitude of the Observer. — In order to n climatic effects of certain additional factor apparent position of the celestial pole as server in any latitude. Since the pole is the axis of the earth, extended, pierces the that, if an observer were at a pole of the e equator would be on his horizon and the c be at his zenith; while, if he were on t earth, the celestial equator would pass t and the celestial poles would be on his south.

Consider an observer at O, Fig. 41, i north of the equator. The line $P'P$

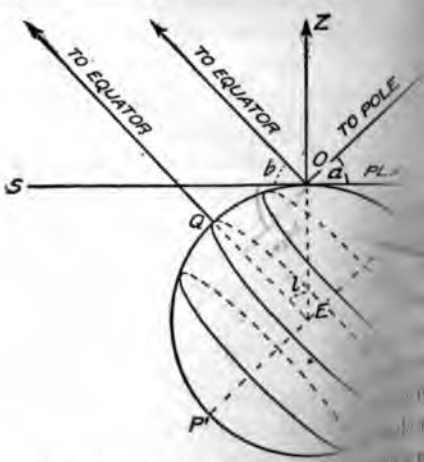


FIG. 41. — The altitude of the celes obse

north pole of the sky. Since compared to the dimension to the celestial pole is essenti between the plane of the h is called the altitude of the

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that the sun is at t
then 23°.5 north of t
this distance from t
path of the sun in this ca
circle parallel to, and 23°
the sun rises north
and sets an equal distan

Suppose the observer is in north latitude 40°
Fig. 43, represent his position, and suppose his
SWNE, where the letters stand for the four card
Then it follows from the relation of the altitud
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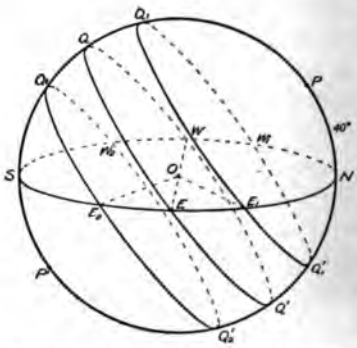


FIG. 43. — Diurnal circles of the sun.

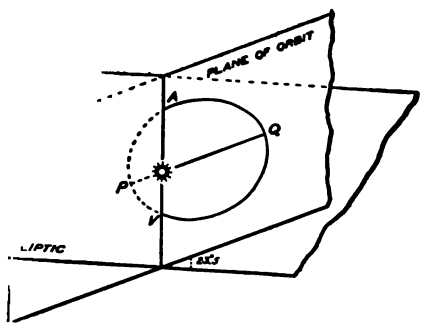
Suppose
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Since it takes six months for it to mov
motion in one day is very small and ma
present discussion. Hence, without se
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is the case, its apparent diurnal path
of the earth, is *EQWQ'*, Fig. 43.
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being exactly half the time above t
time below it. This is true whate
observer. But the height at whic
depends, of course, upon the latitu
greater the nearer he is to the ear

Suppose now that it is June 21
summer solstice *S*, Fig. 42. It
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equator all day. The diurnal
is $E_1Q_1W_1Q_1'$, Fig. 43, which is
north of, the equator. In th
the east point by the angle *E*

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se of the eccentricity of the earth's orbit, summers in the thern hemisphere are longer than the winters.

iameter of the sun that the earth is at its peri-
r about January 3, and at its aphelion on or about
It follows from the way the earth describes its
s explained in Art. 54, that the time required for it
ve from P to Q, Fig. 44, is exactly equal to that
red for it to move from Q to P. But the line joining
vernal and autumnal equinoxes, which passes through
sun, is nearly at right angles to the line joining the
rihelion and aphelion points, and is represented by VA,
Fig. 44. Since the area swept over by the radius from the sun to the earth, while the earth is moving over the arc

the surface perpendicularly. The intensity of sunligh
the earth's equator when the sun is at the zenith is
times its maximum intensity at the earth's poles; and
amount received per unit area on the equator in a w
year is about 2.5 times that received at the poles.

If the obliquity of the ecliptic were zero, the sun w
pass every day through the zenith of an observer at
earth's equator; but actually, it passes through the ze
only twice a year. Consequently, the effect of the obliq
of the ecliptic is to diminish the amount of heat receive
the earth's equator. Therefore some other places on
earth, which are obviously the poles, must receive a l
amount than they would if the equator and the ec
were coincident. That is, the obliquity of the e
causes the climate to vary less in different latitudes t
would if the obliquity were zero.

60. Lag of the Seasons. — From the astronomica
of view March 21 and September 23, the times at wh
sun passes the two equinoxes are corresponding
The middle of the summer is when the sun is at the
solstice, June 21, and the middle of the winter wh
the winter solstice, December 21. But from the
standpoint March 21 and September 23 are not c
ing seasons, and June 21 and December 21 a
middle of summer and winter respectively. Th
seasons lag behind the astronomical.

The cause of the lag of the seasons is very
June 21 any place on the earth's surface north o
of Cancer is receiving the largest amount of h
any time in the year. On account of the bla
of the atmosphere, less heat is radiated tha
hence the temperature continues to rise. T
date less and less heat is received as day
on the other hand, more is radiated daily, f
body gets, the faster it radiates. In a few
equals, and then exceeds, that which is rec

VQA, is greater than the area descri… to the the arc *APV*, it follows that the interv… ena mer case is greater than that in the … erved *V* is the vernal equinox, the summer … for the sphere is longer than the winter. T… eralize is greatly exaggerated in the figure, … with interval from vernal equinox to autu… more about 186.25 days, while that fro… goreans vernal equinox is only 179 days. … tributions fore, about 7.25 days.

Since the summers are longer … thod; for, northern hemisphere while the re… servation, ern hemisphere, it might be supp… introduced sponding latitudes receive more … though often sphere than in the southern … d that the noticed from Fig. 44 that, altho… the universe, the northern hemisphere than … crystalline is then farther from the sun.

cussion of the way in which … 409–356 B.C.), sun varies and from the ra… 310–250 B.C.), ent points in its orbit, that … modern sense of the northern hemisphere … to secure perfect greater distance the earth … theory. Aris- is that points in correspon… ent motions of the equator receive in … by the theory amount of light and heat … olves around the

There is, however, a di… eory were true ern and southern hemis… rections at differ- centricity of the earth's … us was that the the celestial equator … wer to a sensible northern latitudes mos… the Alexandrian that tends to produce … and to which the tance of the sun redu… had the formal temperature does not … school where geometry if the earth's orbit … has required almost the same place, when …

The rather formal astronomy which resulted from the influence of the mathematics of Alexandria was succeeded by an epoch in which the greatest care was taken to secure observations of the highest possible precision. Hipparchus (180–110 B.C.), who belonged to this period, is universally conceded to have been the greatest astronomer of antiquity. His observations in both extent and accuracy had never been approached before his time, nor were they again equaled until the time of the Arab, Albategnius (850–929 A.D.). He systematically and critically compared his observations with those of his predecessors. He developed trigonometry without which precise astronomical calculations cannot be made. He developed an ingenious scheme of eccentrics and epicycles (which will be explained presently) to represent the motions of the heavenly bodies.

Ptolemy (100–170 A.D.) was the first astronomer of note after Hipparchus, and the last important astronomer of the Alexandrian period. From his time until that of Copernicus (1473–1543) not a single important advance was made in the science of astronomy. From Pythagoras to Ptolemy was 700 years, from Ptolemy to Copernicus was 1400 years, and from Copernicus to the present time is 400 years. The work of Ptolemy, which is preserved in the *Almagest* (i.e. The Greatest Composition), was the crowning achievement of the second period, and that of Copernicus was the first of the modern period; or, perhaps it would be more accurate to say that the work of Copernicus constituted the transition from ancient to modern astronomy, which was really begun by Kepler (1571–1630) and Galileo (1564–1642).

The most elaborate theory of ancient times for explaining the motions of the heavenly bodies was due to Ptolemy. He supposed that the earth was a fixed sphere situated at the center of the universe. He supposed that the sun and moon moved around the earth in circles. It does not seem to have occurred to the ancients that the orbits of the heavenly bodies could be anything but circles, which were supposed

respecting the meanings of these motions d... ...ies varying dis-
very dawn of history. Many of the sim... ...ed by the vari-
of the sun, moon, and planets had been e... ...posed that the
by the Chaldeans and Egyptians, but it ... ...circles in which
brilliant and imaginative Greeks to organ... ...around it. It is
experience and to develop theories. Thal... ...would have
having introduced Egyptian astronomy ... ...around a body
than 600 years before the Christian era.
followed a century later and made impo... ...the purpose of ex-
to the philosophy of the science, but v... ...the epicycle. In
Their success was due to the weakness o... ...with uniform
not being too much hampered by the ... ...whose center moved
they gave free rein to their imagina... ...the deferent, around
numerous ideas into a budding science ... ...dimensions and in-
erroneous, later led to the truth. T... ...deferent, together with
earth was round, immovable, at the c... ...succeeded in getting
and that the heavenly bodies moved ... ...motions of the sun, moon,
spheres.

Following the Pythagoreans came ... ...known.
Aristotle (384–322 B.C.), and Ari... ...skillful, observer,
who were much more scientific, ...of his life to the study of the
the term, and who made serious a... ...bodies with a view to
agreement between the observa... ...The invention of printing
tarchus was the first to show tha... ...the writings of the Greek
the sun, moon, and stars could ... ...gradually became convinced
that the earth rotates on its axi... ...sun is the center, and that the
sun. Aristotle's objection was t... ...and revolves around the sun,
the stars would appear to be in d... ...way all the observed phe-
ent times of the year; the reply ... ...that Copernicus had no rigorous
stars were infinitely remote, a... ...but the great merit of his work
criticism. Aristarchus was a ... ...and minute care with which
school, founded by Alexander ... ...theory would satisfy the
geometer Euclid belonged. H... ...theory, and that from
perfection which would be nat... ...it was much more plausible.
was so splendidly systematize... ...Copernicus was Tycho Brahe
no modification for 2000 year... ...heliocentric theory both for
...because he could not observe any

stars due to the annual motion of the
nted nothing of value to the theory of
was an observer of tireless industry whose
been equaled in quality or quantity. For
rained the length of the year correctly to
ond of time.

time of Tycho Brahe and that of Newton
who finally laid the whole foundation for me-
rticularly the theory of motions of the planets,
wo great astronomers, Galileo (1564–1642) and
71–1630), who by work in quite different direc-
the complete overthrow of the Ptolemaic theory
rs and epicycles. These two men had almost no
ties in common. Galileo was clear, penetrating,
Kepler was mystical, slow, but endowed with un-
g industry. Galileo, whose active mind turned in
directions, invented the telescope and the pendulum
to some extent anticipated Newton in laying the
ation of dynamics, proved that light and heavy bodies
the same rate, covered the field of mathematical and
ical science, and defended the heliocentric theory in a
chless manner in his *Dialogue on the Two Chief Systems*
the World. Kepler confined his attention to devising a
eory to account for the apparent motions of sun and planets,
pecially as measured by his preceptor, Tycho Brahe. With
n honesty and thoroughness that could not be surpassed,
he tested one theory after another and found them unsatis-
factory. Once he had reduced everything to harmony ex-
cept some of the observations of Mars by Tycho Brahe
(of course without a telescope), and there the discrepancy
was below the limits of error of all observers except Tycho
Brahe. Instead of ascribing the discrepancies to minute
errors by Tycho Brahe, he had implicit faith in the absolute
reliability of his master and passed on to the consideration
of new theories. In his books he set forth the complete
record of his successes and his failures with a childlike candor

considerable similarity to motion in a
at one of its foci.

Another device used by Ptolemy
plaining the motions of the planets
this system the body was supposed
speed along a small circle, the epicycl
with uniform speed along a large circl
the earth. By carefully adjusting th
clinations of the epicycle and the de
the rates of motion along them, Ptolem
a very satisfactory theory for the moti
and planets so far as they were then k

Copernicus was not a great, or eve
but he devoted many years of his lif
apparent motions of the heavenly bo
discovering their real motions. The
about 1450 had made accessible the w
philosophers, and Copernicus gradual
that the suggestion that the sun is the
earth both rotates on its axis and revo
explains in the simplest possible way
nomena. It must be insisted that Cope
proof that the earth revolves

not found in any other writer. After
of computation he found the three laws
(Art. 145) which paved the way for N
owes much to the thoroughness of Kepl

VI. QUESTIONS

1. Note carefully the position of any con
and verify the fact that in a month it will be
same time in the evening.

2. From which of the laws of motion d
attracting bodies revolve around their comm

3. What are the fundamental principles
four proofs of the revolution of the earth
really independent proofs of the revolution o

4. Which of the proofs of the revolution
the size of its orbit?

5. The aberration of light causes a star a
small curve near its true place; what is the
the star is at the pole of the ecliptic? If it
earth's orbit?

6. Discuss the questions corresponding
small curve described as a consequence of
Do aberration and parallax have their max
same times, or are their phases such that th

7. Discuss the climatic conditions if the
as it is at present.

8. If the eccentricity of the earth's or
respects would the seasons differ from those

9. If the inclination of the equator to t
what respects would the seasons differ from th

10. Suppose the inclination of the equa
90°; describe the phenomena which would
and to our seasons.

11. Draw diagrams giving the diurnal cir
sun is at an equinox and both solstices, for a
equator, in latitude 75° north, and at the no

12. At what times of the year is the sun
southward slowest (see Fig. 42)? For what
through or near the zenith? This place w
temperature. Compare the amount of he
received by the equator during an equal i
near the equinox. Which will have the hig

Although the celestial bodies differ greatly in di
from the earth, some being millions of times as far a
others, they all seem to be at about the same distar
spherical surface, which is called the *celestial sph*
fact, the ancients actually assumed that the star
tached to a crystalline sphere. The celestial spher
sphere at any particular large distance; it is an
surface beyond all the stars and on which they s
jected, at such an enormous distance from the
two lines drawn toward a point on it from any
on the earth, or from any two points on the e
are so nearly parallel that their convergence
detected with any instrument. For short, it
an infinite sphere.

While the real problem giving rise to refere
lines is that of describing accurately and con
tions of celestial objects from the observer
equivalent to describing their apparent
celestial sphere. Since it is much easier to
on a sphere than it is to think of the direct
ing from its center, the heavenly bodies a
tion by describing their projected positi
sphere. Fortunately, a similar problem
locating positions on the surface of the
nomical problem is treated similarly.

consists of
and the
are called
from which
one which
the pole of
the point
of the earth,
the celestial
is called the

64. The Geographical System. — E
with the method of locating a position
earth by giving its latitude and longi
be sufficient to point out here the es
process.

nates of a point
system are (*a*)
distance above or
horizon, which is
altitude, and (*b*) the
distance west from
point along the
circle through the
called the *azimuth* of

The geographical lines that cover
of two distinct sets which have q
The first set consists of the equato
and the parallels of latitude, whic
to the equator. If the equator i
two associated poles, which are 90

of the observer,

enith. The point where the
rfectly definite and is repre-
The vertical circle which passes
dian. The points at which the
re the north and south points.
ions in the northern hemisphere
rest the pole *P*. In this way the
uely defined.

Its altitude is *BA*, which, in this
its azimuth is *SWNEB*, which, in
300°. It is, of course, understood that
be below the horizon and the azimuth
from zero to 360°. When the object is
its altitude is considered as being positive,
as being negative.

uator System. — The poles of the sky have
the points where the earth's axis prolonged
celestial sphere. It might be supposed at
ese would not be conspicuous points because the
is a line which of course cannot be seen. But
tion of the earth causes an apparent motion of
around the pole of the sky. Consequently, an
good definition of the poles is that they are the
on centers of the diurnal circles of the stars. That
which is visible from the position of an observer is a
no less conspicuous than the zenith.

The celestial equator is a great circle 90° from the poles of the sky. An alternative definition is that the celestial equator is the great circle in which the plane of the earth's equator intersects the celestial sphere. The small circles parallel to the celestial equator are called *declination circles*.

The second set of circles in the equatorial system consists of those which pass through the poles and are perpendicular to the celestial equator. They are called *hour circles*. The fundamental hour circle, called the *equinoctial colure*, from which all others are measured, is that one which passes

face, and on the sea it is alwa
small altitude above the sur
reason it is called the sensibl
the astronomical horizon, wi
paragraph.

The direction defined by
is perfectly definite. The
extended upward, pierces
zenith, and the opposite poi
points will be taken as pol
the horizon system, and
circle on the celestial sph
circles parallel to the h
sometimes, almucantars.

The second set of cir
the great circles whic
nadir and cut the hori
vertical circles. The f
distances along the h

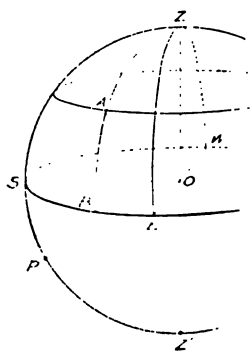


Fig. 45. The h

horizon to the p
object crosses t
the object.

In Fig. 45, O

67. **The Ecliptic System.** — The third system which is employed in astronomy, but much less frequently than the other two, is known as the ecliptic system because the fundamental circle in its first set is the ecliptic. The *ecliptic* is the great circle on the celestial sphere traced out by the sun in its apparent annual motion around the sky. The points on the celestial sphere 90° from the ecliptic are the poles of the ecliptic. The small circles parallel to the ecliptic are called *parallels of latitude*. The great circles which cross the ecliptic at right angles are called *longitude circles*.

The coördinates in the ecliptic system are the angular distance north or south of the ecliptic, which is called *latitude*, and the distance eastward from the vernal equinox along the ecliptic to the point where the longitude circle through the object intersects the ecliptic, which is called *longitude*.

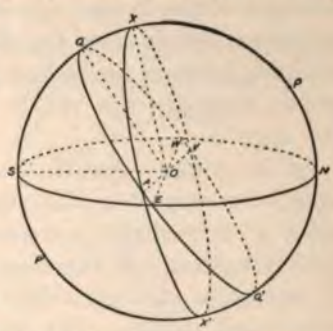


FIG. 47. — The ecliptic system.

In Fig. 47, O represents the position of the observer and $QEQ'W$ the celestial equator. Suppose that at the time in question the vernal equinox is at V and that the autumnal equinox is at A. Then, since the angle between the ecliptic and the equator is 23°.5, the position of the ecliptic is $AX'VX$.

68. **Comparison of the Systems of Coördinates.** — All three of the systems of coördinates are geometrically like the one used in geography; but there are important differences in the way in which they arise and in the purposes for which their use is convenient.

The horizon system depends upon the position of the observer and the direction of his plumb line. It always has the same relation to him, and if he travels he takes it with him. The equator system is defined by the apparent

through the vernal equinox, that is, the place at whi
sun in its apparent annual motion around the sky
the celestial equator from south to north.

The coördinates in the equator system are (*a*) the
distance north or south of the celestial equator, which
declination, and (*b*) the angular distance eastward
vernal equinox along the equator to the point
hour circle through the object crosses the equat
distance is called *right ascension*. The direction e
defined as that in which the sun moves in it
motion among the stars.

In Fig. 46, let O represent the position of t
$NESW$ his horizon, PNQ Q his meridian.

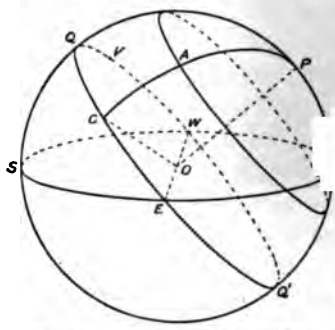


FIG. 46. — The equator system.

star is at A and
nal equinox is at
declination of t
arc CA and its
is VQC. In thi
lination is abo
right ascensio
It is not cust
the right asce
but to give i
an hour equ
present case
sion of A is, therefore, about 5 hours.

It is easy to understand why it is c
right ascension in hours. The sky has
westward because of the earth's actua
and it makes a complete circuit of 360°
fore it apparently moves westward
follows that a simple method of findi
of an object is to note when the vern
meridian and to measure th time w
object is observed to cross
time is its right ascension e

rotation of the sky, which is due, of course, to rotation of the earth, and it is altogether inde the position of the observer. The ecliptic systen by the apparent motion of the sun around the s is independent of the position of the observer.

Since the horizon system depends upon the the observer, the altitude and azimuth of an o really locate it unless the place of the obser Since the stars have diurnal motions across the of day must also be given; and since different meridian at different times on succeeding d that the day of the year must also be give venience of the horizon system arises from circles are not fixed on the sky. Yet it is in observer because the horizon is approximate which separates the visible from the inv the sky.

In the equator system the reference poi fixed with respect to the stars. This sta requires two slight corrections. In the earth's equator, and therefore the celestial to precession (Art. 47). In the second pl very small motions with reference to become appreciable in work of extreme in the course of a few years. But in th these motions will be neglected and the will be considered as being absolutel to the stars. With this understanding of an object is fully defined if its right tion are given. The reference points system also have the desirable quali respect to the stars.

From what has been said it mig equator and ecliptic systems are such is by no means the case. The the meridian at an altitude which

clear from Figs. 48 and 49 that the position of
with respect to the horizon system changes conti
the apparent rotation of the sky. It follows th
purposes the ecliptic system is not convenien
in astronomy is limited almost entirely to des
position of the sun, which is always on the e
the positions of the moon and planets, which
near it.

69. Finding the Altitude and Azimuth when Ascension, Declination, and Time are Given. the right ascension and declination of a star ar
that its altitude and azimuth are desired. It
also to have given the latitude of the observer,
day, and the time of year, because the altitude
depend on these quantities. Most of the diff
problem arises from the fact that the vernal
diurnal motion around the sky and that it is
is not easily located. By computing the rig
the sun at the date in question, direct us
equinox may be avoided. It has been fou
solve the problem in four distinct steps.

Step 1. The right ascension of the sun on
— It has been found by observation
the vernal equinox March 21. (The d
because of the leap year, but it will b
for the present purposes to use Marc
a year the sun moves around the sky
sion, or at the rate of two hours a
rate of apparent motion of the sun
the variations from it are small an
present connection. It follows
right ascension of the sun on a
counting the number of month
in question and multiplying
ample, October 6 is 6.5 m
right ascension of the sun

afternoon can be equally well called 14 o'c
right ascension is called 26 hours, the rule
the result that the hour angle is 4 hours ea

Step 4. Application of the declination a
the altitude and azimuth. — In order to ma
clear, consider a special example. Suppose
of the object
by Step 3 to
This locates t
51. Therefo
somewhere on
PCP'. The
tion determi
star is on th
pose, for exa
object is 35° n
to locate it, it
sary to me
from C along
Hence the s

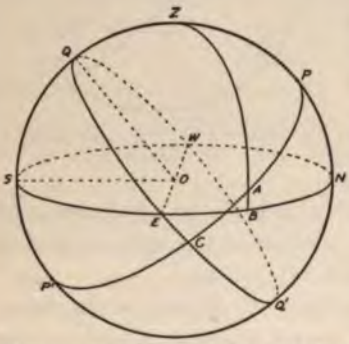


FIG. 51. — Application of the declination in finding the position of a star.

Now draw a vertical circle from Z through A
at B. The altitude is BA and the azimu
These distances can be computed by spherical
but they may be estimated closely

explained in Art. 69, an
Suppose the observer is in
the pole P, Fig. 52, a
and the point Q, where
will have an alti-
. Suppose the date
the observation is
June 21 and the time
8 P.M. Suppose the
ascension of the star
is approximately
and that its declina-
$-16°$. The problem
its apparent altitude
azimuth.

The steps of the
will be made in their
order. (1) Since June
the right ascension
(2) Since the time
counted eastward
$6 + 8 = 14$ hours
is 16 hours, its
hour circle PQP
16° south from
a vertical circle
The altitude
$SWNEB$.

71. Finding the
the Altitude and
finding the
and azi
Art.
In the
and
found



in Art. 69. The third step is to draw through the position of the given object an hour circle which, from its definition, reaches from one pole of the sky to the other and cuts the equator at right angles. The fourth step is to estimate the hour angle of the hour circle drawn in Step 3 and the distance of the star from the equator measured along the hour circle. Then the right ascension of the object is equal to the right ascension of the meridian plus the hour angle of the object if it is east, and minus the hour angle if it is west; and the declination of the object is simply its distance from the equator.

72. Illustrative Example for Finding Right Ascension and Declination. — Suppose the date of the observation is May 6 and that the time of day is 8 P.M. Suppose the observer's latitude is 40° north. Suppose he sees a bright star whose altitude is estimated to be 35° and whose azimuth is estimated to be 60°. Its right ascension and declination are required, and after they have been obtained it can be found from Table I, p. 144, what star is observed.



FIG. 53. — Finding the right ascension and declination.

The right ascension of the sun on May 6 is 3 hours and the right ascension of the meridian at 8 P.M. is 11 hours. The star then is at the point A, Fig. 53, where $BA = 35°$ and $SB = 60°$. The part of the vertical circle BA is much less foreshortened than AZ by the projection of the celestial sphere on a plane, and this fact must be remembered in connection with the drawing. The hour circle PAP' cuts the equator at the point C. The arc QC is much more foreshortened by projection than CW. Consequently, it is seen that the hour angle of the star is 3.5 hours west. Therefore

its right ascension is $11-3.5=7.5$ hours approximately. It is also seen that the star is approximately 5° north of the equator. On referring to Table I, it is found that this star must be Procyon.

All problems of the same class can be solved in a similar manner. But reliance should not be placed in the diagrams alone, especially because of the distortion to which certain of the lines are subject. The diagrams should be supplemented, if not replaced, by actually pointing out on the sky the various points and lines which are used. A little practice with this method will enable one to solve either the problem of finding the altitude and azimuth, or that of obtaining the right ascension and declination, with an error not exceeding 5° or 10°.

73. Other Problems Connected with Position. — There are two other problems of some importance which naturally arise. The first is that of finding the time of the year at which a star of given right ascension will be on the meridian at a time in the evening convenient for observation.

In order to make the problem concrete, suppose the time in question is 8 P.M. The right ascension of the sun is then 8 hours less than the right ascension of the meridian. Since the object is supposed to be on the meridian, the right ascension of the sun will be 8 hours less than that of the object. To find the time of the year at which the sun has a given right ascension, it is only necessary to count forward from March 21 two hours for each month. For example, if the object is Arcturus, whose right ascension is 14 hours, the right ascension of the sun is $14-8=6$ hours, and the date is June 21.

The second problem is that of finding the time of day at which an object whose right ascension is given will be on the meridian or horizon on a given date. A problem of this character will naturally arise in connection with the announcement of the discovery of a comet or some other object whose appearance in a given position would be con-

spicuous only for a short time. This problem is solv first finding the right ascension of the sun on the dat then taking the difference between this result and th ascension of the object. This gives the hour angle sun at the required time. If the sun is west of the me its hour angle is the time of day; if it is east of the me its hour angle is the number of hours before noon.

VII. QUESTIONS

1. Make a table showing the correspondences of the circles, and coördinates of the horizon, equator, and ecliptic with those of the geographical system.

2. What are the altitude and azimuth of the zenith, point, the north pole? What are the angular distances f zenith to the pole and to the point where the equator cr meridian in terms of the latitude l of the observer?

3. Estimate the horizon coördinates of the sun at 10 o'c morning; at 10 o'clock this evening.

4. Describe the complete diurnal motions of stars near What part of the sky for an observer in latitude 40° is alwa the horizon? Always below the horizon?

5. How long is required for the sky apparently to Through what angle does it apparently turn in 1 minute?

6. Are there positions on the earth from which th motions of the stars are along parallels of altitude? Alon circles?

7. Develop a rule for finding the hour angle of t equinox on any date at any time of day.

8. Find the altitude and azimuth of the vernal e 9 A.M. to-day.

9. Given: Rt. asc. = 19 hrs., declination = + 20°, date time = 8 P.M.; find the altitude and azimuth.

10. Find the altitude and the azimuth (constructing of each of the stars given in Table I, p. 144, at 8 P.M. to-d

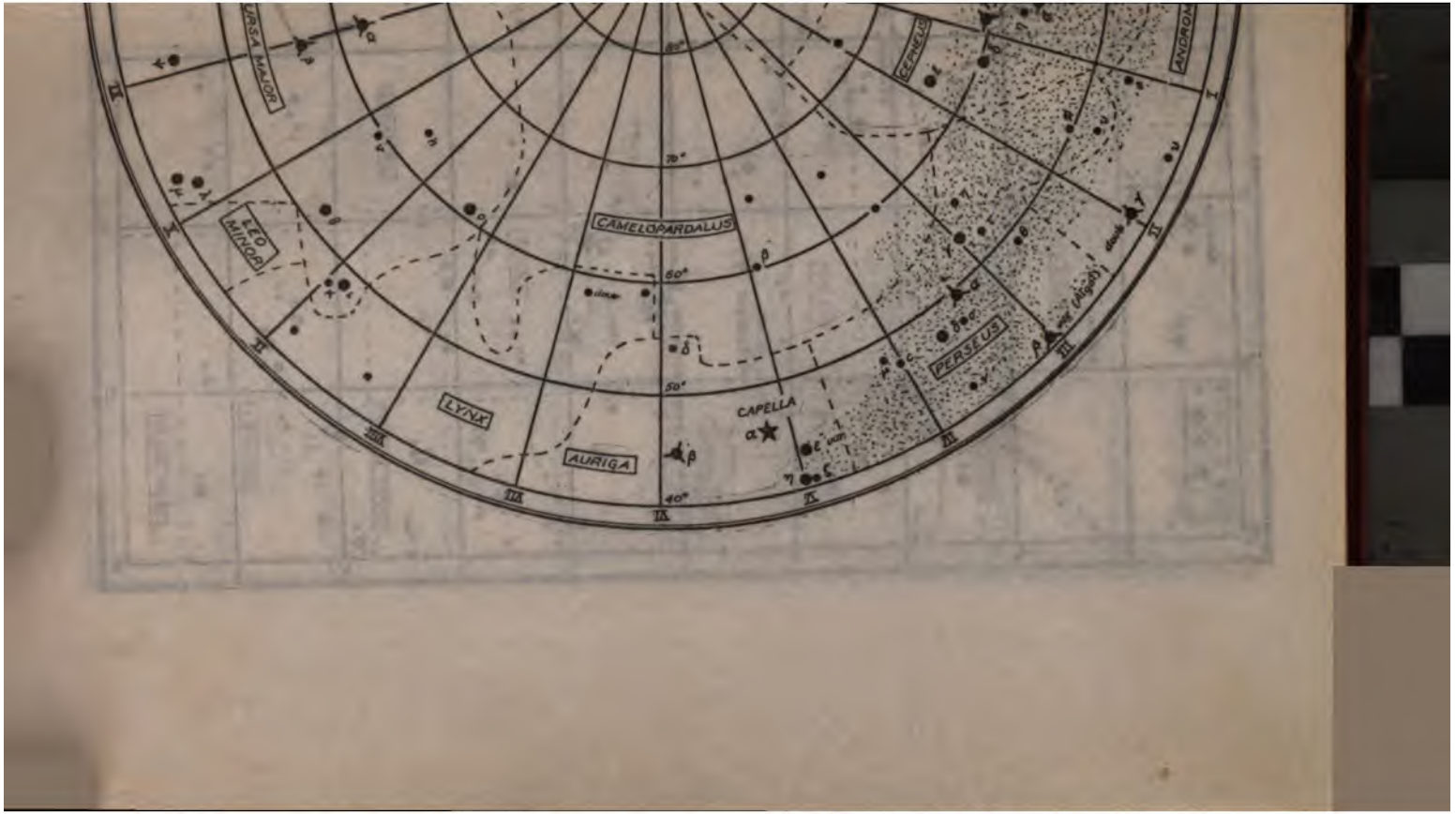
11. If a star whose right ascension is 18 hours is on th at 8 P.M., what is the date?

12. At what time of the day is a star whose right a 14 hours on the meridian on May 21?

13. At what time of the day does a comet whose righ is 4 hours and declination is zero rise on Sept. 21?

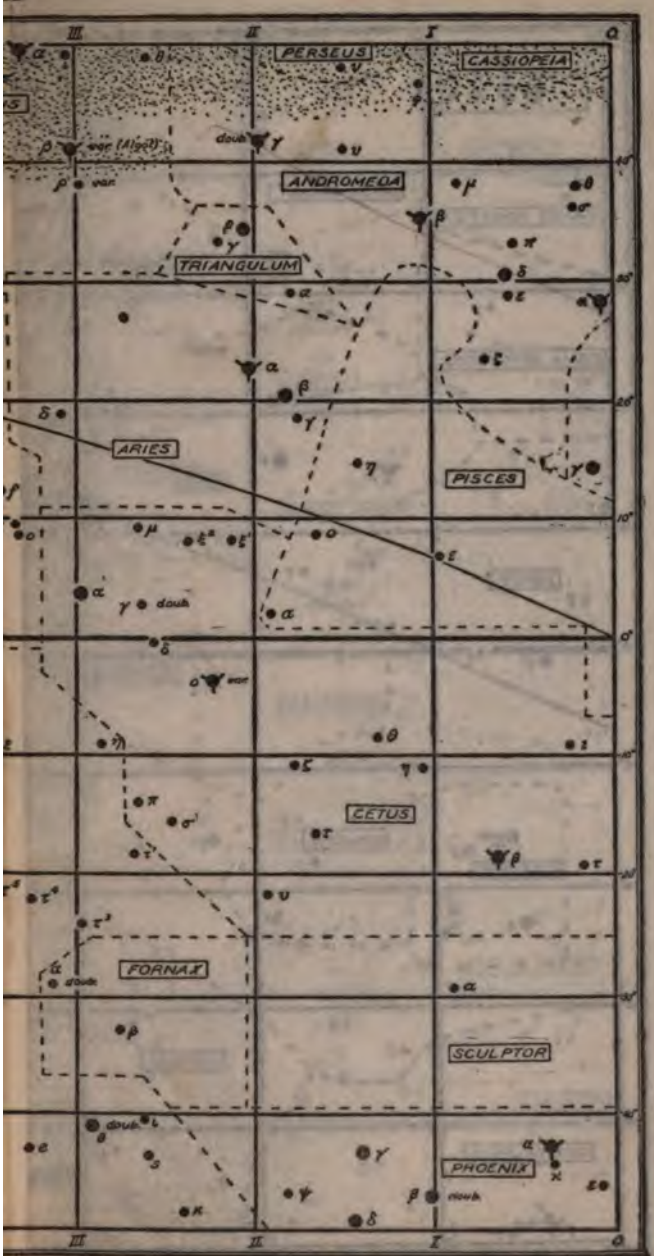
14. The Leonid meteors have their radiant at righ

MAG: 1 2 3 4
LACERTA
CYGNUS
LYRA
DRACO
HERCULES
URSA MINOR
BOOTES
CANES VENATICI
PATH OF POLE

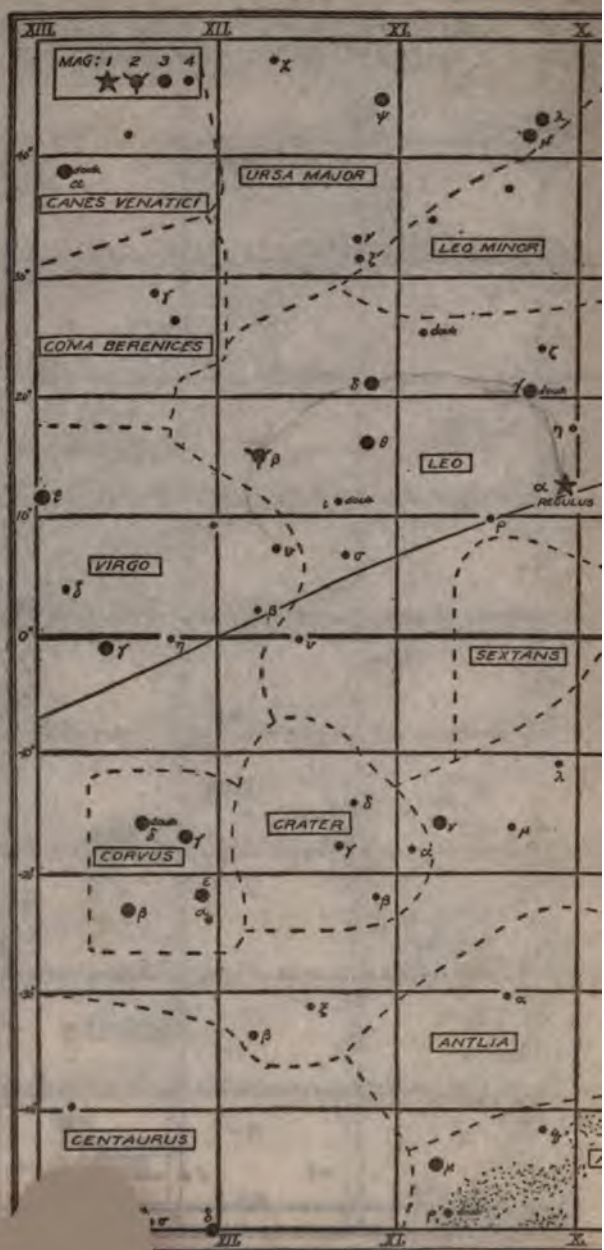

URSA MAJOR
LEO MINOR
CAMELOPARDALUS
LYNX
AURIGA
CAPELLA
PERSEUS
CEPHEUS
ANDROM
80°
70°
60°
50°
40°
XII
I
II
III
IX


CAPELLA
AURIGA
GEMINI
TAURUS
HYADES
ALDEBARAN
ORION
BETELGEUSE
RIGEL
LEPUS
CANIS MAJOR
CANIS MINOR
MONOCEROS
HYDRA

II.

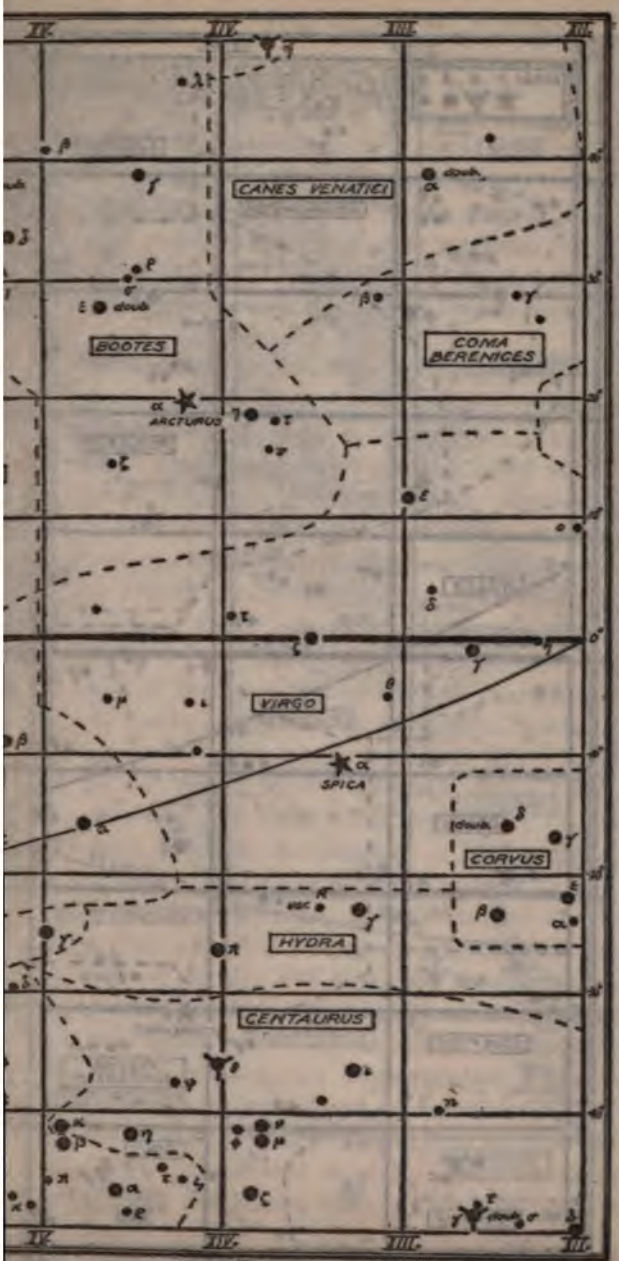

III
II
I
O
PERSEUS
CASSIOPEIA
ANDROMEDA
TRIANGULUM
ARIES
PISCES
CETUS
FORNAX
SCULPTOR
PHOENIX
var
double
nebula




XIII.
XII.
XI.
X.
MAG: 1 2 3 4
CANES VENATICI
URSA MAJOR
LEO MINOR
COMA BERENICES
LEO
REGULUS
VIRGO
SEXTANS
CRATER
CORVUS
ANTLIA
CENTAURUS
+40°
+30°
+20°
+10°
0°
-10°
-20°
-30°
-40°

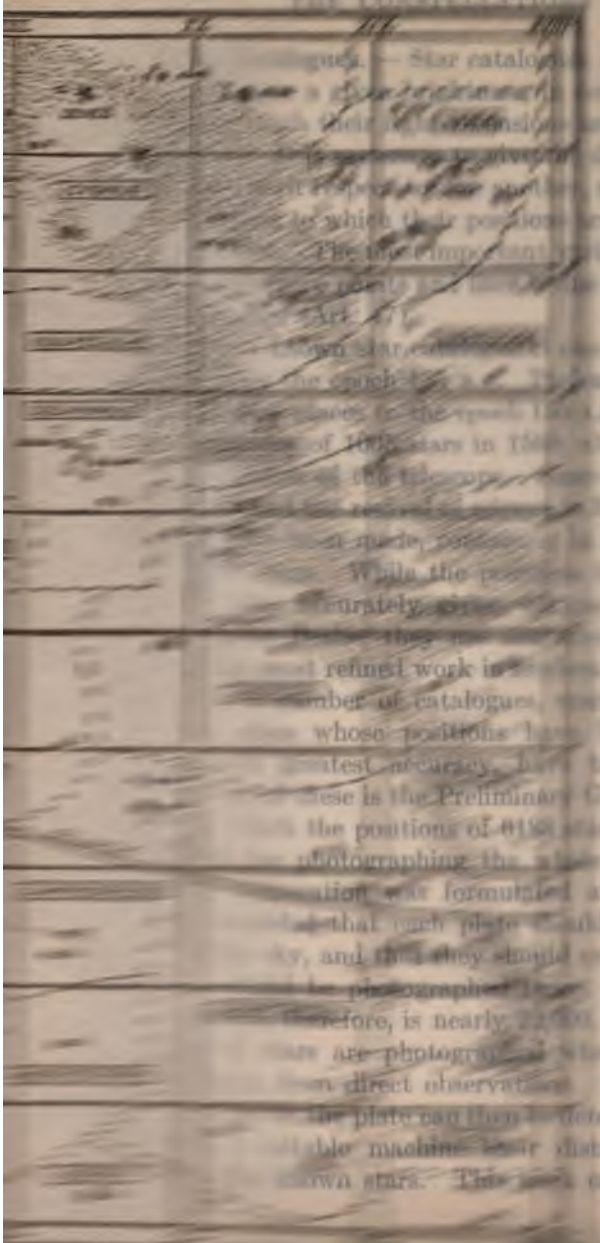

IX.
VIII.
VII.
VI.
LYNX
AURIGA
CASTOR
POLLUX
GEMINI
CANCER
CANIS MINOR
ORION
PROCYON
MONOCEROS
ARGO: PUPPIS
SIRIUS
CANIS MAJOR
COLUMBA
IX.
VIII.
VII.
VI.




CANES VENATICI
BOOTES
COMA BERENICES
ARCTURUS
VIRGO
SPICA
CORVUS
HYDRA
CENTAURUS

CANES VENATICI
BERENICES
COMA
BOOTES
VIRGO
SPICA
CORVUS
HYDRA
CENTAURUS


MAG: 1 2 3 4
LACERTA
ANDROMEDA
PEGASUS
PISCES
CETUS
SCULPTOR
GRUS



LYRA
CYGNUS
HERCULES
CORONA BOREALIS
ARIETIS
PERSEUS
CAPRICORNUS
ECLIPTIC
SAGITTARIUS
SCORPIUS
VIRGO

76. Star Catalogues. — Star catalogues are lists of stars, usually all above a given brightness, in certain parts of the sky, together with their right ascensions and declinations on a given date. It is necessary to give the date, for the stars slowly move with respect to one another, and the reference points and lines to which their positions are referred are not absolutely fixed. The most important variation in the position of the reference points and lines is due to the precession of the equinoxes (Art. 47).

The earliest known star catalogue is one of 1080 stars by Hipparchus for the epoch 125 B.C. Ptolemy revised it and reduced the star places to the epoch 150 A.D. Tycho Brahe made a catalogue of 1005 stars in 1580, about 30 years before the invention of the telescope. Since the invention of the telescope and the revival of science in Europe, numerous catalogues have been made, containing in some cases more than 100,000 stars. While the positions in all these catalogues are very accurately given, compared even to the work of Tycho Brahe, they are not accurate enough for certain of the most refined work in modern times. To meet these needs, a number of catalogues, containing a limited number of stars whose positions have been determined with the very greatest accuracy, have been made. The most accurate of these is the Preliminary General Catalogue of Boss, in which the positions of 6188 stars are given.

A project for photographing the whole heavens by international coöperation was formulated at Paris in 1887. The plan provided that each plate should cover 4 square degrees of the sky, and that they should overlap so that the whole sky would be photographed twice. The number of plates required, therefore, is nearly 22,000. On every plate a number of stars are photographed whose positions are already known from direct observations. The positions of the other stars on the plate can then be determined by measuring with a suitable machine their distances and directions from the known stars. This work can, of course, be

carried out at leisure in an astronomical laboratory. On these plates, most of which have already been secured, there will be shown in all about 8,000,000 different stars. In the first catalogue based on them only about 1,300,000 of the brightest stars will be given.

The photographic catalogue was an indirect outgrowth of photographs of the great comet of 1882 taken by Gill at the Cape of Good Hope. The number of star images obtained on his plates at once showed the possibilities of making catalogues of stars by the photographic method. In 1889 he secured photographs of the whole southern sky from declination $-19°$ south, and the enormous labor of measuring the positions of the 350,000 star images on these plates was carried out by Kapteyn, of Groningen, Holland.

77. The Magnitudes of the Stars. — The magnitude of a star depends upon the amount of light received from it by the earth, and is not determined altogether by the amount of light it radiates, for a small star near the earth might give the observer more light than a much larger one farther away. It is clear from this fact that the magnitude of a star depends upon its actual brightness and also upon its distance from the observer.

The stars which are visible to the unaided eye are divided arbitrarily into 6 groups, or magnitudes, depending upon their apparent brightness. The 20 brightest stars constitute the first-magnitude group, and the faintest stars which can be seen by the ordinary eye on a clear night are of the sixth magnitude, the other four magnitudes being distributed between them so that the ratio of the brightness of one group to that of the next is the same for all consecutive magnitudes. The definition of what shall be exactly the first magnitude is somewhat arbitrary; but a first-magnitude star has been taken to be approximately equal to the average brightness of the first 20 stars. The sixth-magnitude stars are about $\frac{1}{100}$ as bright as the average of the first group, and, in order to make the ratio from one magnitude

to the other perfectly definite, it has been agreed that the technical sixth-magnitude stars shall be those which are exactly $\frac{1}{100}$ as bright as the technical first-magnitude stars. The problem arises of finding what the ratio is for successive magnitudes.

Let r be the ratio of light received from a star of one magnitude to that received from a star of the next fainter magnitude. Then stars of the fifth magnitude are r times brighter than those of the sixth, and those of the fourth are r times brighter than those of the fifth, and they are therefore r^2 times brighter than those of the sixth. By a repetition of this process it is found that the first-magnitude stars are r^5 times brighter than those of the sixth magnitude. Therefore $r^5 = 100$, from which it is found that $r = 2.512\ldots$.

Since the amount of light received from different stars varies almost continuously from the faintest to the brightest, it is necessary to introduce fractional magnitudes. For example, if a star is brighter than the second magnitude and fainter than the first, its magnitude is between 1 and 2. A step of one tenth of a magnitude is such a ratio that, when repeated ten times, it gives the value 2.512. . . . It is found by computation, which can easily be carried out by logarithms, that a first-magnitude star is 1.097 times as bright as a star of magnitude 1.1. The ratio of brightness of a star of magnitude 1.1 to that of a star of 1.2 is likewise 1.097; and, consequently, a star of magnitude 1 is $1.097 \times 1.097 = 1.202$ times as bright as a star of magnitude 1.2.

A star which is 2.512 times as bright as a first-magnitude star is of magnitude 0, and still brighter stars have negative magnitudes. For example, Sirius, the brightest star in the sky, has a magnitude of -1.58, and the magnitude of the full moon on the same system is about -12, while that of the sun is -26.7.

78. The First-magnitude Stars. — As first-magnitude stars are conspicuous and relatively rare objects, they serve

as guideposts in the study of the constellations. All of those which are visible in the latitude of the observer should be identified and learned. They will, of course, be recognized partly by their relations to neighboring stars.

In Table I the first column contains the names of the first-magnitude stars; the second, the constellations in which they are found; the third, their magnitudes according to the Harvard determination; the [illegible] their right ascensions; the fifth, their declinations; [illegible], the dates on which they cross the meridian at 8 [illegible] and the seventh, the velocity toward or from the e[illegible] miles per second, the negative sign indicating ap[illegible] the positive, recession. Their apparent positions a[illegible]e can be determined from their right ascensions [illegible] declinations by the principles explained in Art. 69.

TABLE I

NAME	CONSTELLATION	MAGNITUDE	RIGHT ASCENSION	DECLINATION	ON MERIDIAN AT 8 P.M.	RADIAL VELOCITY
Sirius	Canis Major	−1.6	6h 41m	−16° 36′	Feb. 28	− 5.6
Canopus	Carina	−0.9	6 22	−52 39	Feb. 23	+12.7
Alpha Centauri	Centaurus	0.1	14 34	−60 29	June 29	−13.8
Vega	Lyra	0.1	18 34	+38 42	Aug. 30	− 8.5
Capella	Auriga	0.2	5 10	+45 55	Feb. 5	+19.7
Arcturus	Boötes	0.2	14 12	+19 37	June 24	− 2.4
Rigel	Orion	0.3	5 11	− 8 17	Feb. 5	+13.6
Procyon	Canis Minor	0.5	7 35	+ 5 26	Mar. 14	− 2.5
Achernar	Eridanus	0.6	1 35	−57 40	Dec. 16	+10.0
Beta Centauri	Centaurus	0.9	13 58	−59 58	June 21	?
Betelgeuse	Orion	0.9	5 51	+ 7 24	Feb. 15	+13.0
Altair	Aquila	0.9	19 47	+ 8 39	Sept. 19	−20.5
Alpha Crucis	Crux	1.1	12 22	−62 38	May 29	+ 4.3
Aldebaran	Taurus	1.1	4 31	+16 21	Jan. 26	+34.2
Pollux	Gemini	1.2	7 40	+28 14	Mar. 15	+ 2.4
Spica	Virgo	1.2	13 21	−10 44	June 12	+ 1.2
Antares	Scorpius	1.2	16 24	−26 15	July 27	− 1.9
Fomalhaut	Piscis Australis	1.3	22 53	−30 4	Nov. 8	+ 4.2
Deneb	Cygnus	1.3	20 39	+44 59	Oct. 4	− 2.5
Regulus	Leo	1.3	10 4	+12 23	Apr. 23	− 5.0

79. Number of Stars in the First Six Magnitudes. — The number of stars in each of the first six magnitudes is given in Table II. The sum of the numbers is 5000.

TABLE II

First Magnitude . . .	20	Fourth Magnitude. . .	425
Second Magnitude. . .	65	Fifth Magnitude . . .	1100
Third Magnitude . . .	190	Sixth Magnitude . . .	3200

There are, therefore, in the whole sky only about 5000 stars which are visible to the unaided eye. At any one time only half the sky is above the horizon, and those stars which are near the horizon are largely extinguished by the absorption of light by the earth's atmosphere. Therefore one never sees at one time more than about 2000 stars, although the general impression is that they are countless.

It is seen from the Table II that the number of stars in each magnitude is about three times as great as the number in the preceding magnitude. This ratio holds approximately down to the ninth magnitude, and in the first nine magnitudes there are in all nearly 200,000 stars. Since a telescope 3 inches in aperture will show objects as faint as the ninth magnitude, it is seen what enormous aid is obtained from optical instruments. Only a rough guess can be made respecting the number of stars which are still fainter, but there are probably more than 300,000,000 of them within the range of present visual and photographic instruments.

80. The Motions of the Stars. — The stars have motions with respect to one another which, in the course of immense ages, appreciably change the outlines of the constellations, but which have not made important alterations in the visible sky during historic times. Nevertheless, they are so large that they must be taken into account when using star catalogues in work of precision.

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Name
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Canopus
Alpha Centauri
Vega
Capella
Arcturus
Rigel
Procyon
Achernar
Beta Centauri
Betelgeux
Altair
Alpha Crucis
Aldebaran
Pollux
Spica
Antares
Fomalhaut
Deneb
Regulus

The Milky Way is a ...to the unaided eye of ...the average about 20° ...great circle entirely around ... it is made up of millions ...guished separately only ...because of its irregular ...cannot be precisely de- ...location is defined by the ...equator at two places ...ly 6 hours 40 minutes ...has an inclination to the

equator of about 62°. Or, in other terms, the north pole of the Milky Way is at right ascension about 12 hours 40 minutes and at declination about + 28°. For a long distance it is divided more or less completely into two parts, and at one place in the southern heavens it is cut entirely across by a dark streak. A very interesting feature for observers in northern latitudes is a singular dark region north of the star Deneb.

82. The Constellations and Their Positions. — The work on reference points and lines in the preceding chapter together with the discussions so far given in this chapter are sufficient to prepare for the study of the constellations with interest and profit, and the student should not stop short of an actual acquaintance with all the first-magnitude stars and the principal constellations that are visible in his latitude. Table III contains a list of the constellations and gives their positions. The numbers at the top show the degrees of declination between which the constellations lie, the numerals at the left show their right ascensions, and the numbers placed in connection with the names of the constellations give the number of stars in them which are easily visible to the unaided eye. The constellations which lie on the ecliptic, or the so-called zodiacal constellations, are printed in italics.

The following maps show the constellations from the north pole to −50° declination. When Map I is held up toward the sky, facing north, with its center in the line joining the eye with the north pole, and with the hour circle having the right ascension of the meridian placed directly above its center, it shows the circumpolar constellations in their true relations to one another and to the horizon and pole. The other maps are to be used, facing south, with their centers held on a line joining the eye to the celestial equator, and with the hour circle having the right ascension of the meridian held in the plane of the eye and the meridian. When they are placed in this way, they show the constellations to the south of the observer in their true relationships. In

TABLE III

R. A. \ DEC.	+90° TO +50°	+50° TO +25°	+25° TO 0°	0° TO −25°	−25° TO −50°	−50° TO −90°
I–II	Cassiopeia, 46.	Andromeda, 18. Triangulum, 5.	*Pisces*, 18; *Aries*, 17.	Cetus, 37.	Phœnix, 32; Apparatus Sculptoris, 13.	(Phœnix); Hydrus, 18.
III–IV . . .	——	Perseus, 46.	*Taurus*, 58.	Eridanus, 64.	(Eridanus.)	Horologium, 11; Reticulum, 9.
V–VI . . .	Camelo-pardalis, 36.	Auriga, 35.	Orion, 58; *Gemini*, 33.	Lepus, 18.	Columba, 15.	Dorado, 16; Pictor, 14; Mons Mensa, 12.
VII–VIII . .	——	Lynx, 28.	Canis Minor, 8; *Cancer*, 15.	Canis Major, 27; Monoceros, 12.	Argo-Navis, 149.	(Argo-Navis, Puppis); Piscis Volans, 9.
IX–X . . .	——	Leo Minor, 15.	*Leo*, 47.	Hydra, 49; Sextans, 5.	——	(Argo-Navis, Vela.)
XI–XII . .	Ursa Major, 53.	——	Coma Berenices, 20.	Crater, 15; Corvus, 8.	Cen 56.	(Argo-Navis, Carina); Chameleon, 13.
XIII–XIV .	——	Canes Venatici, 15; Boötes, 36.	——	*Virgo*, 39.	Lu[illegible]	(Centaurus); Crux, 13; Musca, 15.
XV–XVI . .	Ursa Minor, 23.	Corona Borealis, 19; Hercules, 65.	Serpens, 25.	*Libra*, 23.	Norma, 14.	Circinus, 10.
XVII–XVIII .	Draco, 80.	Lyra, 18.	Aquila, 37; Sagitta, 5.	*Scorpius*, 34; Ophiuchus, 46.	Ara, 15	Triangulum Australe, 11; Apus, 8.
XIX–XX . .	——	Cygnus, 67.	Vulpecula, 23; Delphinus, 10.	*Sagittarius*, 48.	Corona Australis, 8.	Telescopium, 16; Pavo, 37; Octans, 22.
XXI–XXII .	Cepheus, 44.	Lacerta, 16.	Equuleus, 5.	*Capricornus*, 22.	Piscis Australis, 16.	Indus, 15; (Octans).
XXIII–XXIV	——	——	Pegasus, 43.	*Aquarius*, 36.	Grus, 30.	(Octans); Tucana, 22.

order to apply the maps according to these instructions, it is necessary to know the right ascension of the meridian for the day and hour in question, and it can be computed with sufficient approximation by the method of Art. 69.

83. Finding the Pole Star. — The first step to be taken in finding the constellations, either from their right ascensions and declinations or from star maps, is to determine the north-and-south line. It is defined closely enough for present purposes by the position of the pole star.

The Big Dipper is the best known and one of the most conspicuous groups of stars in the northern heavens. It is always above the horizon for an observer in latitude 40° north, and, because of its definite shape, it can never be mistaken for any other group of stars. It is made up of 7 stars of the second magnitude which form the outline of a great dipper in the sky. Figure 56 is a photograph of this group of stars distinctly showing the dipper. The stars Alpha and Beta are called The Pointers because they are almost directly in a line with the pole star Polaris. In order to find the pole star, start with Beta, Fig. 55, go through Alpha, and continue about five times the distance from Beta to Alpha. At the point reached there will be found the second-magnitude star Polaris with no other one so bright anywhere in the neighborhood.



FIG. 56. — The Big Dipper.

Besides defining the north-and-south line and serving as a guide for a study of the constellations in the northern heavens, the pole star is an interesting object in several other respects. It has a faint companion of the ninth magnitude, distant from it about 18.5 seconds of arc. This

TABLE III

R. A. \ Dec.	+90° to +50°	+50° to +25°	+25° to 0°	0° to −25°	−25° to −50°	−50° to −90°
I–II	Cassiopeia, 46.	Andromeda, 18. Triangulum, 5.	*Pisces*, 18; *Aries*, 17.	Cetus, 37.	Phœnix, 32; Apparatus Sculptoris, 13.	(Phœnix); Hydrus, 18.
III–IV	——	Perseus, 46.	*Taurus*, 58.	Eridanus, 64.	(Eridanus.)	Horologium, 11; Reticulum, 9.
V–VI	Camelopardalis, 36.	Auriga, 35.	Orion, 58; *Gemini*, 33.	Lepus, 18.	Columba, 15.	Dorado, 16; Pictor, 14; Mons Mensa, 12.
[illegible]	——	Lynx, 28.	Canis Minor, 8; *Cancer*, 15.	Canis Major, 27; Monoceros, 12.	Argo-Navis, 149.	(Argo-Navis, Puppis); Pleris Volans, 9.
[illegible]	——	[illegible]	*Leo*, 47.	Hydra, 49; Sextans, 6.	——	(Argo-Navis, Vela.)
[illegible]	——	[illegible]	[illegible]	Crater, 15; Corvus, 8.	Centaurus, 58.	(Argo-Navis, Carina); Chamæleon, 13. (Centaurus); Crux, 13; Musca, 13.
[illegible]	——	[illegible]	[illegible]	[illegible]	Lupus, 41.	[illegible]

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The most conspicuous configurations in the northern heavens, is in the eastern part[1] of the constellation Ursa Major and serves to locate the position of this constellation. The outline of the Bear extends north, south, and west of the bowl of the Dipper for more than 10°; but all the stars in this part of the sky are of the third magnitude or fainter.

According to the Greek legend, Zeus changed the nymph Callisto into a bear in order to protect her from the jealousy of his wife Hera. While the transformed Callisto was wandering in the forest, she met her son Arcas, who was about to slay her when Zeus intervened and saved her by placing them both among the stars, where they became the Greater and the Smaller Bears. Hera was still unsatisfied and prevailed on Oceanus and Thetis to cause them to pursue forever their courses around the pole without resting beneath the ocean waves. Thus was explained the circumpolar motions of those stars which are always above the horizon.

The Pawnee Indians call the stars of the bowl of the Dipper a stretcher on which a sick man is being carried, and the first one in the handle is the medicine man.

The star at the bend of the handle of the Dipper, called Mizar by the Arabs, has a faint one near it which is known as Alcor. Mizar is of the second magnitude, and Alcor is of the fifth. Any one with reasonably good eyes can see the two stars as distinct objects, without optical aid. It is probable that this was the first double star that was discovered. The distance of 11′.5 between them is so great, astronomically speaking, that it is no longer regarded as a true double star. It has been supposed by some writers that the word Alcor is derived from an Arabic word meaning the test, and the

[1] East and west on the sky must be understood to be measured along declination circles. Consequently, near the pole east may have any direction with respect to the horizon. Above the pole, east on the sky is toward the eastern part of the horizon, while below the pole it is toward the western part of the horizon. All statements of direction in descriptions of the constellations refer to directions on the sky unless otherwise indicated, and care must be taken not to understand them in any other sense.

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of its second part, and a 2-inch telescope will show that it is a double star whose colors are described as rose and blue.

One of the most interesting objects in this constellation is the star Eta Cassiopeiæ, which is near the middle of the third stroke of the *W* and about 2° from Alpha. It is a fine double which can be separated with a 3-inch telescope. The two stars are not only apparently close together, but actually form a physical system, revolving around their common center of gravity in a period of about 200 years. If there are planets revolving around either of these stars, their phenomena of night and day and their seasons must be very complicated.

In 1572 a new star suddenly blazed forth in Cassiopeia and became brighter than any other one in the sky. It caught the attention of Tycho Brahe, who was then a young man, and did much to stimulate his interest in astronomy.

87. How to Locate the Equinoxes. — It is advantageous to know how to locate the equinoxes when the positions of objects are defined by their right ascensions and declinations. To find the vernal equinox, draw a line from Polaris through the most westerly star in the *W* of Cassiopeia, and continue it 90°. The point where it crosses the equator is the vernal equinox which, unfortunately, has no bright stars in its neighborhood.

If the vernal equinox is below the horizon, the autumnal equinox may be conveniently used. One or the other of them is, of course, always above the horizon. To find the autumnal equinox, draw a line from Polaris through Delta Ursæ Majoris, or the star where the handle of the Big Dipper joins the dipper, and continue it 90° to the equator. The autumnal equinox is in Virgo. This constellation contains the first-magnitude star Spica, which is about 10° south and 20° east of the autumnal equinox.

88. Lyra (The Lyre, or Harp). — Lyra is a small but very interesting constellation whose right ascension is about 18.7 hours and whose declination is about 40° north. It is,

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the early Greeks, or any primitive peoples. A century ago astronomers gave their ability to separate this pair without the use of the telescope as proof of their having exceptionally keen sight. Perhaps with the more exacting use to which the eyes of the human race are being subjected, they are actually improving instead of deteriorating as is commonly supposed.

Although the angular distance between the two components of Epsilon Lyræ seems small, astronomers regularly measure one two-thousandth of this angle. The discovery of Neptune was based on the fact that in 60 years it had pulled Uranus from its predicted place, as seen from the earth, only a little more than half of the angular distance between the components of this double star. When Epsilon Lyræ is viewed through a telescope of 5 or 6 inches' aperture, it presents a great surprise. The two components are found to be so far apart in the telescope that they can hardly be seen at the same time, and a little close attention shows that each of them also is a double. That is, the faint object Epsilon Lyræ is a magnificent system of four suns.

About 5°.5 south of Vega and 3° east is the third-magnitude star Beta Lyræ. It is a very remarkable variable whose brightness changes by nearly a magnitude in a period of 12 days and 22 hours. The variability of this star is due to the fact that it is a double whose plane of motion passes nearly through the earth so that twice in each complete revolution one star eclipses the other. A detailed study of the way in which the light of this star varies shows that the components are stars whose average density is approximately that of the earth's atmosphere at sea level.

About 2°.5 southeast of Beta Lyræ is the third-magnitude star Gamma Lyræ. On a line joining these two stars and about one third of the distance from Beta is a ring, or annular, nebula, the only one of the few that are known that can be seen with a small telescope. It takes a large telescope, however, to show much of its detail.

89. Hercules (The Kneeling Hero). — Hercules is a very large constellation lying west and southwest of Lyra. It contains no stars brighter than the third magnitude, but it can be recognized from a trapezoidal figure of 5 stars which are about 20° west of Vega. The base of the trapezoid, which is turned to the north and slightly to the east, is about 6° long and contains two stars in the northeast corner which are of the third and fourth magnitudes. The star in the southeast corner is of the fourth magnitude, and the others are of the third magnitude. On the west side of the trapezoid, about one third of the distance from the north end, is one of the finest star clusters in the whole heavens, known as Messier 13. It is barely visible to the unaided eye on a clear dark night, appearing as a little hazy star; but through a good telescope it is seen to be a wonderful object, containing more than 5000 stars (Fig. 171) which are probably comparable to our own sun in dimensions and brilliancy. The cluster was discovered by Halley (1656–1742), but derives its present name from the French comet hunter Messier (1730–1817), who did all of his work with an instrument of only 2.5 inches' aperture.

90. Scorpius (The Scorpion). — There are 12 constellations, one for each month, which lie along the ecliptic and constitute the zodiac. Scorpius is the ninth of these and the most brilliant one of all. In fact, it is one of the finest group of stars that can be seen from our latitude. It is 60° straight south of Hercules and can always be easily recognized by its fiery red first-magnitude star Antares, which, in light-giving power, is equal to at least 200 suns such as ours. The word Antares means opposed to, or rivaling, Mars, the red planet associated with the god of war. Antares is represented as occupying the position of the heart of a scorpion. About 7″ west of Antares is a faint green star of the sixth magnitude which can be seen through a 5- or 6-inch telescope under good atmospheric conditions. About 5° northwest of Antares is a very compact and fine cluster,

Messier 80. Scorpius lies in one of the richest and most varied parts of the Milky Way.

According to the Greek legend, Scorpius is the monster that killed Orion and frightened the horses of the sun so that Phaëton was thrown from his chariot when he attempted to drive them.

91. Corona Borealis (The Northern Crown). — Just west of the great Hercules lies the little constellation Corona Borealis. It is easily recognized by the semicircle, or crown, of stars of the fourth and fifth magnitudes which opens toward the northeast. The Pawnee Indians called it the camp circle, and it is not difficult to imagine that the stars represent warriors sitting in a semicircle around a central campfire.

92. Boötes (The Hunter). — Boötes is a large constellation lying west of Corona Borealis, in right ascension about 14 hours, and extending from near the equator to within 35° of the pole. It always can be easily recognized by its bright first-magnitude star Arcturus, which is about 20° southwest of Corona Borealis. This star is a deep orange in color and is one of the finest stars in the northern sky. It is so far away that 100 years are required for its light to come to the earth, and in radiating power it is equivalent to more than 500 suns like our own.

In mythology Boötes is represented as leading his hunting dogs in their pursuit of the bear across the sky.



FIG. 57. — The sickle in Leo, as seen when it is on the meridian.

93. Leo (The Lion). — Leo lies about 60° west of Arcturus and is the sixth zodiacal constellation. It is easily recognized by the fact that it contains 7 stars which form the outline of a sickle. In the photograph, Fig. 57, only the 5 brightest stars are shown. The most southerly star of



FIG. 68.—The Great Andromeda Nebula. *Photographed by Ritchey with the two-foot reflector of the Yerkes Observatory.*

the sickle is Regulus, at the end of the handle. The blade of the sickle opens out toward the southwest. One of the most interesting things in connection with this constellation is that the meteors of the shower which occurs about November 14 seem to radiate from a point within the blade of the sickle (Art. 204).

The star Regulus is at the heart of the Nemean lion which, according to classic legends, was killed by Hercules as the first of his twelve great labors.

94. Andromeda (The Woman Chained). — Andromeda is a large constellation just south of Cassiopeia. It contains no first-magnitude stars, but it can be recognized from a line of 3 second-magnitude stars extending northeast and southwest. The most interesting object in this constellation is the Great Andromeda Nebula, Fig. 58, the brightest nebula in the sky. It is about 15° directly south of Alpha Cassiopeiæ, and it can be seen without difficulty on a clear, moonless night as a hazy patch of light. When viewed through a telescope it fills a part of the sky nearly 2° long and 1° wide. In its center is a star which is probably variable. The analysis of its light with the spectroscope seems to indicate that it is composed of solid or liquid material surrounded by cooler gases. It has been suggested that, instead of being a nebula, it may be an aggregation of millions of suns comparable to the Galaxy, but so distant from us that it apparently covers an insignificant part of the sky.

95. Perseus (The Champion). — Perseus is a large constellation in the Milky Way directly east of Andromeda. Its brightest star, Alpha, is in the midst of a star field which presents the finest spectacle through field glasses or a small telescope in the whole sky. The second brightest star in this constellation is the earliest known variable star, Algol (the Demon). Algol is about 9° south and a little west of Alpha Persei, and varies in magnitude from 2.2 to 3.4 in a period of 2.867 days. That is, at its minimum it loses more than two thirds of its light. There is also a remarkable



FIG. 58. — The Great Andromeda Nebula.
the two-foot reflector of the Yerkes

double clust... ...mber
Cassiopeiæ. ...ings ...
Algol, tog... ...ion ...
head which ... ...n of th...
he used in ...
stirred up ... ...bserved
pears as th... ...the group
96. Aurig ...While their
east of Pe... ...y be less
magnitude ...that these
Big Dippe ...so remote.
Ursæ Ma... ...would ap-
near it a... ...magnitude.
meaning ... ...00 to 200
of nearly
times th... ...s group, a
Lick Ob... ...ythology.
a period ... ...cluster of
show th... ...ove in the
given o... ...Art. 277).
97. T... ...e beyond
and co... ...ty from 5
and th... ...the space
Amo... ...the dis-
lation
on Ori... ...arus and
of a b... ...on, lying
While ... ...s of right
upon ... ...e sky for
hims...
away ... ...air details
the ... ...a mighty
cove... ...arus) with
T...
form... ...east of Al-
near... ...southwest of

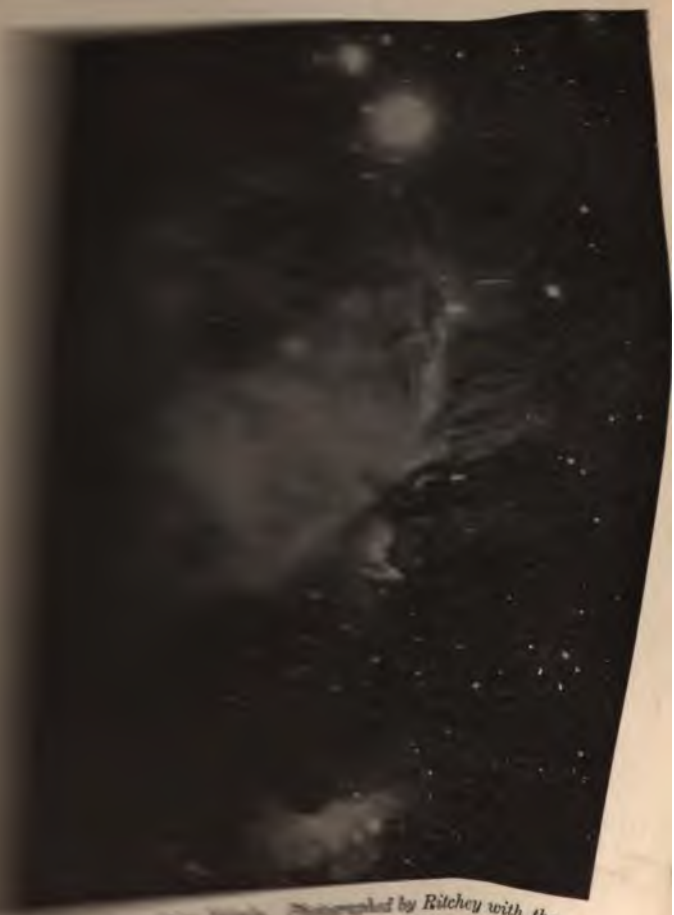
Betelgeuze is the first-magnitude star Rigel, a magnificent object which is at least 2000 times as luminous as the sun. About midway between Betelgeuze and Rigel and almost on the equator is a row of second-magnitude stars running northwest and southeast, which constitute the Belt of Orion, Fig. 60. From its southern end another row of fainter stars reaches off to the southwest, nearly in the direction of



FIG. 60. — Orion. *Photographed at the Yerkes Observatory (Hughes).*

Rigel. These stars constitute the Sword of Orion. The central one of them appears a little fuzzy without a telescope, and with a telescope is found to be a magnificent nebula, Fig. 61. In fact, the Great Orion Nebula impresses many observers as being the most magnificent object in the whole heavens. It covers more than a square degree in the sky, and the spectroscope shows it to be a mass of glowing gas whose distance is probably several million times as great as that to the sun, and whose diameter is probably as great as

at that
17, no
ancient
the rel
Austral
Besid
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which
distan
than 10
stars
A star
pear
The la
times
Also
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They
stars,
same
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to 100
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Photographed by Ritchey with the
Yerkes Observatory.

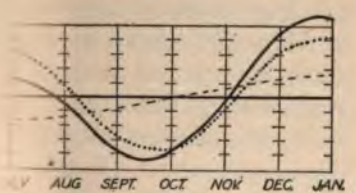
and a considerable fraction of them

99. Canis Major (The Greater Dog). — The constellation Canis Major is southeast of Orion and is marked by Sirius, the brightest star in the whole sky. Sirius is almost in a line with the Belt of Orion and a little more than 20° from it. It is bluish white in color and is supposed to be in an early stage of its evolution, though it has advanced somewhat from the condition of the Orion stars. Sirius is comparatively near to us, being the third star in distance from the sun. Nevertheless, 8.4 years are required for its light to come to us, and its distance is 47,000,000,000,000 miles. It is approaching us at the rate of 5.6 miles per second; or, rather, it is overtaking the sun, for the solar system is moving in nearly the opposite direction.

The history of Sirius during the last two centuries is very interesting, and furnishes a good illustration of the value of the deductive method in making discoveries. First, Halley found, in 1718, that Sirius has a motion with respect to fixed reference points and lines; then, a little more than a century later, Bessel found that this motion is slightly variable. He inferred from this, on the basis of the laws of motion, that Sirius and an unseen companion were traveling around their common center of gravity which was moving with uniform speed in a straight line. This companion actually was discovered by Alvan G. Clark, in 1862, while adjusting the 18-inch telescope now of the Dearborn Observatory, at Evanston, Ill. The distance of the two stars from each other is 1,800,000,000 miles, and they complete a revolution in 48.8 years. The combined mass of the two stars is about 3.4 times that of the sun. The larger star is only about twice as massive as its companion but is 20,000 times brighter; together they radiate 48 times as much light as is emitted by the sun.

100. Canis Minor (The Lesser Dog). — Canis Minor is directly east of Orion and is of particular interest in the present connection because of its first-magnitude star Procyon, which is about 25° east and just a little south of Betel-

he earth moves forward
from Fig. 62, in which
rth when it is noon at A.
the earth has moved for-
E_1SE_2 (of course the dis-
ppose that when the earth
E_0S. When the earth is at
The sun has apparently
which equals E_2SE_1.
rbit in accordance with the
fastest when it is nearest



line gives effects of eccentricity;
line, the combined effects.

the earth is at its perihelion
ward is fastest, and the solar
e is concerned, are then the
rihelion point about the first
point about the first of July.
noon to noon, so far as it
f the earth's orbit, is longest
d shortest about the first of
r days, so far as they depend
rth's orbit, are shown by the

on why the solar days vary
es eastward along the ecliptic
For simplicity, neglect the
and the lack of uniformity of
n along the ecliptic. Consider

earth's orbit on that equal intervals of sidereal tim
equal according to the first law of motion.

106. Solar Time. — Solar time is defined by the ro
of the earth with respect to the sun. A solar day
interval of time between the passage of a meridian
the center of the sun and its next succeeding passage
the center of the sun. Since the sun apparently
eastward among the stars, a solar day is longer tha
sidereal day. The sun makes an apparent revolution
heavens in 365 days, and therefore, since the circuit
heavens is 360°, it moves eastward on the average a
less than 1° a day. The earth turns 15° in 1 hour,
in 4 minutes, from which it follows that the solar d
nearly 4 minutes longer on the average than the sidereal

107. Variations in the Lengths of Solar Days. —
apparent motion of the sun eastward among the stars
uniform,
solar day
be longer
the sidereal
by the
amount;
since the sid
days are
equal lengt
solar days
would all
equal len
But the
ward app
motion of

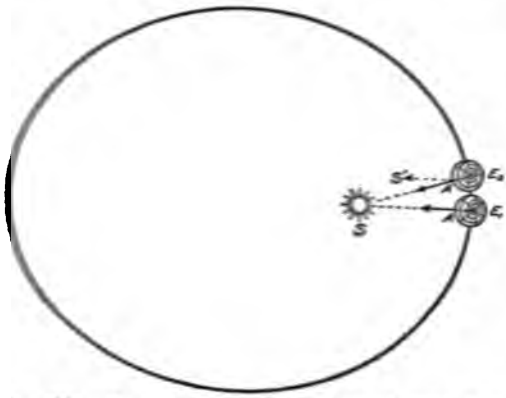


FIG. 62. — Solar days are longer than sidereal days.

sun is somewhat variable because of two principal rea
which will now be explained.

The earth moves in its elliptical orbit around the s
such a way that the law of areas is fulfilled. The an
distance the sun appears to move eastward amon

of the year, is introduced … In order to avoid
24 hours, 3 minutes, and … for all places whose
The mean solar day is … a hour from that of
the hours into 60 mean … to local time of that
60 mean solar seconds. … difference in local time
seconds in common use, … meridian may be
to keep mean solar time … than about half
be very difficult, if not … manner a strip of
would keep true solar time … 35° to 45° uses
108. The Equation of T… …width an hour
true solar time and the … standard meridian
the *equation of time*. It …
that, when it is added to … nearly every civilized
time is obtained.[1] … British America
The date on which mea… …it is necessary to
time shall coincide is ar… …eastern portion uses
… local time of the
… meridian runs
… time and standard
… meridian it is later
… difference being
… of this meridian,
… later by local time
… to the westward
… of the meridian
… through St. Louis.
… Time. It is the
… Greenwich. This
… time division
… of the meridian
… passes about 100

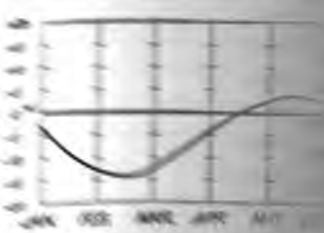


FIG. 61.

differences between the … …boundaries between
as small as possible. On … east and west of
of time is zero. It th… …, the boundaries
numerically until Febru… …convenience of
−14 minutes and 25 … …
through zero about Apri… …
and reaches a value of … …
it then decreases and … …
becomes −6 minutes …

[1] This is the present … …
Almanac. It was formerly …

...ds, and they are frequently somewhat altered. The ... in time is nearly always made at the end of a railway ...on; for, obviously, it would be unwise to have rail- ... time change during the run of a given train crew. As ...sult the actual boundaries of the several time divisions ...quite irregular and vary in many cases radically from the



FIG. 65. — Standard time divisions in the United States.

ideal standard divisions. Moreover, many towns near the borders of the time zones do not use standard time.

111. The Distribution of Time. — The accurate determination of time and its distribution are of much importance. There are several methods by which time may be determined, but the one in common use is to observe the transits of stars across the meridian and thus to obtain the sidereal time. From the mathematical theory of the earth's motion it is then possible to compute the mean solar time. It might be supposed that it would be easier to find mean solar time by observing the transit of the sun across the meridian, but this is not true. In the first place, it is much

fusion and great danger in running trains. In or
these difficulties, it has been agreed that all
local times do not differ more than half an hour
some convenient meridian shall use the local
meridian. Thus, while the extreme difference
of places using the local time of the same me
about an hour, neither of them differs more th
an hour from its standard time. In this ma
country about 750 miles wide in latitudes
the same time, and the next strip of the same
different, and so on. The local time of the sta
of each strip is the *standard time* of that stri

At present standard time is in use in nearl
part of the earth. The United States and
are of such great extent in longitude that
use four hours of standard time. The ea
what is called Eastern Time. It is the
meridian 5 hours west of Greenwich. T
through Philadelphia, and in this city local
time are identical. At places east of this
by local time than by standard time,
one minute for 12 or 13 miles. At places w
but in the Eastern Time division, it is
than by standard time. The next divi
is called Central Time. It is the local
6 hours west of Greenwich, which pass
The next time division is called Mount
local time of the meridian 7 hours west
meridian passes through Denver. T
is called Pacific Time. It is the local
8 hours west of Greenwich. This mer
miles east of San Francisco.

If the exact divisions were used,
one time division and the next would
the standard meridian. As a matter
are quite irregular, depending up

time balls in 18 ports in
for furnishing time, chiefly
large ball which is dropped at
considerable height at con-
electrical connection with the

stern part of the United States
Island Navy Yard in California;
of college observatories have been
ticular railroad systems. Naturally
ularly determine time for their own
accurate distribution of time from
for this work is disappearing except
oblems of star positions.

Astronomical Days. — The civil day begins
hen business is ordinarily suspended and
changed with least inconvenience. The
of the same date begins at noon, 12 hours
If the change were made at midnight, astron-
find it necessary to change the date in the
of observations. It is true that many observa-
un and some other bodies are made in the day-
course most observational work is done at night.
of the astronomical day are numbered up to 24,
he case of sidereal time.

Place of Change of Date. — If one should start at
on the earth and go entirely around it westward,
ber of times the sun would cross his meridian would
less than it would have been if he had stayed at home.
would be very inconvenient for him to use fractional
he would count his day from midnight to midnight,
ever his longitude, and correct the increasing difference
the time of his starting point by arbitrarily changing
date one day forward at some point in his journey. That
he would omit one date and day of the week from his
ckoning. On the other hand, if he were going around the

a day; hence
date line is sh
The sidereal
tly to move f
seen from the
rhaps it is bet
arth to make a
ions from the
the stars. Its
urs, 9 minutes,
25 days.
ear.—The an
rth to move fr
rihelion again.
would equal
her planets cau
uch a rate th
years; and th
a little longer
period of its re
about 12', ann
about a degre
nds of time to
listic year in
es, 53.01 secon
—The tropica
ve from a tro
ter for practic
ame equinox
'.2 annually, th
han the sidereal
s 365 days, 5 h
on the sun's pl
ently, if the se
accordingly to

earth e tward, he would give two days the sa
day of the week. The change is usually made
meridian from Greenwich. This is a particular
selection, for the 180th meridian scarcely passes
land surface at all, and then only small island
easily see how troublesome matters would be i
were made at a meridian passing through a th
lated region, say the meridian of Greenwich.

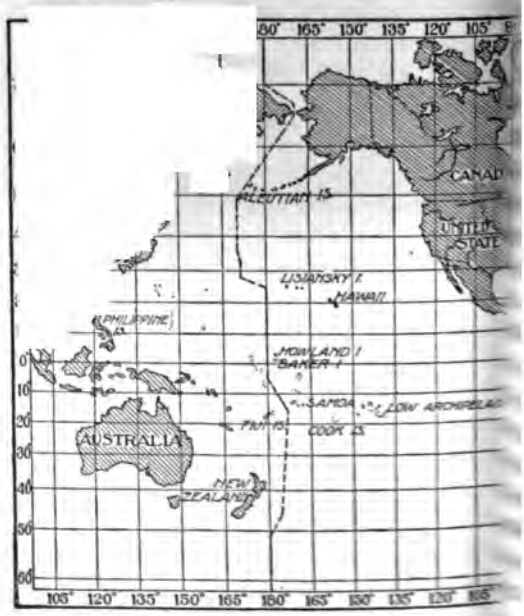


FIG. 66. — The change-of-date line.

of it people would have a certain day and date
Monday, December 24, and on the other sid
later, Tuesday, December 25.

The place of actual change of date does not
the 180th meridian from Greenwich, for tr
eastward from Europe, lose half a day, whil
westward from Europe and America arrive

have given the basis for determining the day of the week on which any date falls, after it has been given in a particular year.

Consider first the problem of finding the day of the week on which January 1 falls. In the year 1900 January 1 fell on Monday. To fix the ideas, consider the question for 1915. If every year had been an ordinary year, January 1 would come one day later in the week each succeeding year, it would have fallen, in 1915, 14 days, or 2 weeks and one day, after Monday; that is, on Tuesday. But, in the meantime there were 3 leap years, namely, 1904, 1908, and 1912, which put the date 3 additional days forward in the week, or on Friday. Similarly, it is seen in general that the rule for finding the day of the week on which January 1 falls in any year of the present century is to take the number of the year in the century (15 in the example just treated), add to it the number of leap years which have passed (which is given by dividing the number of the year by 4 and neglecting the remainder), divide the result by 7 to eliminate the number of weeks which have passed, and finally, count forward from Monday the number of days given by the remainder. For example, in 1935 the number of the year is 35, the number of leap years is 8, the sum of 35 and 8 is 43, and 43 divided by 7 equals 6 with the remainder of 1. Hence, in 1935, January 1 will be one day later than Monday; that is, it will fall on Tuesday.

In order to find the day of the week on which any date of any year falls, find first the day of the week on which January 1 falls; then take the day of the year, which can be obtained by adding the number of days in the year up to the date in question, and divide this by 7; the remainder is the number of days that must be added to that on which January 1 falls in order to obtain the day of the week. For example, consider March 21, 1935. It has been found that January 1 of this year falls on Tuesday. There are 79 days from January 1 to March 21 in ordinary years. If 79 is

the quotient is 11 with the remainder of 2. March 21, 1935, falls 2 days after Tuesday, Thursday.

IX. QUESTIONS

Give examples where intervals of time in which you many and varied intellectual experiences now seem longer intervals of the same length. Have you had any con- experiences?

If the sky were always covered with clouds, how should we time?

What is your sidereal time to-day at 8 P.M.?

What would be the relations of solar time to sidereal time if rotated in the opposite direction?

What is the length of a sidereal day expressed in mean solar

What is the standard time of a place whose longitude is 85° of Greenwich when its local time is 11 A.M.?

What is the local time of a place whose longitude is 112° west Greenwich when its standard time is 8 P.M.?

Suppose a person were able to travel around the earth in 2 ys; what would be the lengths of his days and nights if he traveled om east to west? From west to east?

9. If the sidereal year were in ordinary use, how long before hristmas would occur when the sun is at the vernal equinox?

10. On what days of the week will your birthday fall for the next 2 years?

CHAPTER VII

THE MOON

119. The Moon's apparent Motion among the Stars. — The apparent motion of the moon can be determined by observation without any particular reference to its actual motion. In fact, the ancient Greeks observed the moon with great care and learned most of the important peculiarities of its apparent motion, but they did not know its distance from the earth and had no accurate ideas of the character of its orbit. The natural method of procedure is first to find what the appearances are, and from them to infer the actual facts.

The moon has a diurnal motion westward which is produced, of course, by the eastward rotation of the earth. Every one is familiar with the fact that it rises in the east, goes across the sky westward, and sets in the west. Those who have observed it except in the most casual way, have noticed that it rises at various points on the eastern horizon, crosses the meridian at various altitudes, and sets at various points on the western horizon. They have also noticed that the interval between its successive passages across the meridian is somewhat more than 24 hours.

Observations of the moon for two or three hours will show that it is moving eastward among the stars. When its path is carefully traced out during a whole revolution, it is found that its apparent orbit is a great circle which is inclined to the ecliptic at an angle of 5° 9′. The point at which the moon, in its motion eastward, crosses the ecliptic from south to north is called the *ascending node* of its orbit, and the point where it crosses the ecliptic from north to south is called the *descending node* of its orbit. The attraction of the

sun for the moon causes the nodes continually to regress on the ecliptic; that is, in successive revolutions the moon crosses the ecliptic farther and farther to the west. The period of revolution of the line of nodes is 18.6 years.

120. The Moon's Synodical and Sidereal Periods. — The synodical period of the moon is the time required for it to move from any apparent position with respect to the sun back to the same position again. The most accurate means of determining this period is by comparing ancient and modern eclipses of the sun; for, at the time of a solar eclipse, the moon is exactly between the earth and the sun. The advantages of this method are that, in the first place, at the epochs used the exact positions of the moon with respect to the sun are known; and, in the second place, in a long interval during which the moon has made hundreds or even thousands of revolutions around the earth, the errors in the determinations of the exact times of the eclipses are relatively unimportant because they are divided by the number of revolutions the moon has performed. It has been found in this way that the synodical period of the moon is 29 days, 12 hours, 44 minutes, and 2.8 seconds; or 29.530588 days, with an uncertainty of less than one tenth of a second.

The sidereal period of the moon is the time required for it to move from any apparent position with respect to the stars back to the same position again. This period can be found by direct observations; or, it can be computed from the synodical period and the period of the earth's revolution around the sun. Let S represent the moon's synodical period, M its sidereal period, and E the period of the earth's revolution around the sun, all expressed in the same units as, for example, days. Then $1/M$ is the fraction of a revolution that the moon moves eastward in one day, $1/E$ is the fraction of a revolution that the sun moves eastward in one day, and $1/M - 1/E$ is, therefore, the fraction of a revolution that the moon gains on the sun in its eastward motion in one day. Since the moon gains one complete revolution on the sun in

S days, $1/S$ is also the fraction of a revolution the moon gains on the sun in one day. Hence it follows that

$$\frac{1}{S} = \frac{1}{M} - \frac{1}{E'}$$

from which M can be computed when S and E are known.

It is easy to see that the synodical period is longer than the sidereal. Suppose the sun, moon, and certain stars are at a given instant in the same straight line as seen from the earth. After a certain number of days the moon will have made a sidereal revolution and the sun will have moved eastward among the stars a certain number of degrees. Since additional time is required for the moon to overtake it, the synodical period is longer than the sidereal.

It has been found by direct observations, and also by the equation above, that the moon's sidereal period is 27 days, 7 hours, 43 minutes, and 11.5 seconds, or 27.32166 days. When the period of the moon is referred to, the sidereal period is meant unless otherwise stated.

The periods which have been given are averages, for the moon departs somewhat from its elliptical orbit, primarily because of the attraction of the sun, and to a lesser extent because of the oblateness of the earth and the attractions of the planets. The variations from the average are sometimes quite appreciable, for the perturbations, as they are called, may cause the moon to depart from its undisturbed orbit about 1°.5, and may cause its period of revolution to vary by as much as 2 hours.

121. The Phases of the Moon. — The moon shines entirely by reflected sunlight, and consequently its appearance as seen from the earth depends upon its position relative to the sun. Figure 67 shows eight positions of the moon in its orbit with the sun's rays coming from the right in lines which are essentially parallel because of the great distance of the sun. The left-hand side of the earth is the night side, and similarly the left side of the moon is the dark side.

The small circles whose centers are on the large circle around the earth as a center show the illuminated and unilluminated parts of the moon as they actually are; the accompanying small circles just outside of the large circle show the moon as it is seen from the earth. For example, when the moon is at M_1 between the earth and sun, its dark side is toward the earth. In this position it is said to be *in conjunction*, and the phase is *new*. At M_2 half of the illuminated part of the moon can be seen from the earth, and it is in the *first quarter*. In this position the moon is said to be *in quadrature*. Between the new moon and the first quarter the illuminated part of the moon as seen from the earth is of crescent shape, and its convex side is turned toward the sun.

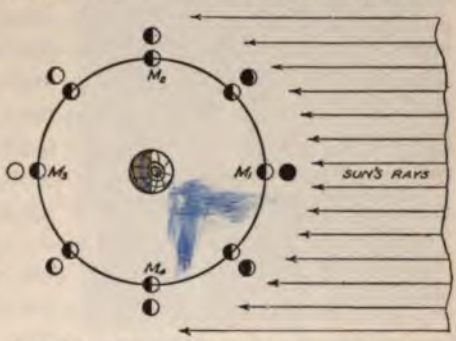


FIG. 67. — Explanation of the moon's phases.

When the moon is at M_3 the illuminated side is toward the earth. It is then *in opposition*, and the phase is *full*. If an observer were at the sunset point on the earth, the sun would be setting in the west and the full moon would be rising in the east. At M_4 the moon is again in quadrature, and the phase is *third quarter*.

To summarize: The moon is new when it has the same right ascension as the sun; it is at the first quarter when its right ascension is 6 hours greater than that of the sun; it is full when its right ascension is 12 hours greater than that of the sun; and it is at the third quarter when its right ascension is 18 hours greater than that of the sun.

It is observed from the diagram that the earth would have phases if seen from the moon. When the moon is

S days. $1/S$ is also [illegible] would be full as seen gains on the sun in [illegible] earth corresponding to [illegible] other position of [illegible] moon can be inferred [illegible] the diagram. The from which M can [illegible]

It is easy to s[illegible] [illegible]ses of the moon and the sidereal. Sup[illegible] [illegible]rth are supplementary; at a given instant [illegible] [illegible]; that is, the illuminated earth. After a [illegible] [illegible]portion of the moon as made a sidereal r[illegible] [illegible]seen from the earth plus ward among the [illegible] [illegible]e illuminated portion of additional time [illegible] [illegible]e earth as seen from the synodical period [illegible] [illegible]moon always equals 180°.

It has been [illegible] [illegible]When the moon is nearly equation above [illegible] [illegible]new, and, consequently, 7 hours, 43 m[illegible] [illegible]the earth nearly full as When the per[illegible] [illegible]seen from the moon, the period is meant [illegible] [illegible]dark side of the moon is

The periodi[illegible] [illegible]reflected from the earth, moon depart[illegible] [illegible]

[illegible] **the Moon.** — Suppose first because of the [illegible] [illegible] ecliptic and consider its because of the [illegible] [illegible]are parallel to the celestial the planets [illegible] quite appreci[illegible] [illegible] may cause th[illegible] [illegible] about 1°.5, [illegible] [illegible] as much as 2°[illegible]



[illegible] and ecliptic.

121. The [illegible] [illegible] the moon in declination between tively by refl[illegible] [illegible] as seen from [illegible] [illegible], it is sufficient, in view of the the sun. [illegible] [illegible] circles (Art. 58), to give the orbit with th[illegible] [illegible] the meridian. Let VAV, are essentia[illegible] [illegible] equator spread out on a plane, sun. The [illegible] [illegible] Suppose, for example, that the similarly th[illegible] [illegible] March 21. Then the sun is at V. If

the moon is new, it is also at V, because at this phase it has the same right ascension as the sun. Since V is on the celestial equator, the moon crosses the meridian at an altitude equal to 90° minus the latitude of the observer. In this case it rises in the east and sets in the west. But if the moon is at first quarter on March 21, it is at S, because at this phase it is 6 hours east of the sun. It is then 23°.5 north of the equator, and, consequently, it crosses the meridian 23°.5 above the equator. In this case it rises north of east and sets north of west. If the moon is full, it is at A, and if it is in the third quarter, it is at W. In the former case it is on the equator and in the latter 23°.5 south of it.

Suppose the sun is at the summer solstice, S. Then it rises in the northeast, crosses the meridian 23°.5 north of the equator, and sets in the northwest. At the same time the full moon is at W, it rises in the southeast, crosses the meridian 23°.5 south of the equator, and sets in the southwest. That is, when sunshine is most abundant, the light from the full moon is the least. On the other hand, when the sun is at the winter solstice W, the full moon is at S and gives the most light. The other positions of the sun and moon can be treated similarly.

Suppose the ascending node of the moon's orbit is at the vernal equinox (Fig. 70), and consider the altitude at which

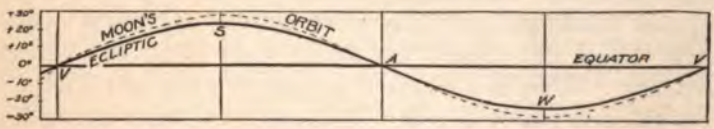


FIG. 70. — Ascending node of the moon's orbit at the vernal equinox.

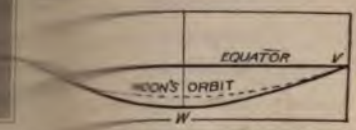
the moon crosses the meridian when full at the time of the winter solstice. The sun is at W and the full moon is in its orbit 5° 9′ north of S. If the latitude of the observer is 40°, the moon then crosses his meridian at an altitude of $50° + 23°.5 + 5° = 78°.5$. That is, under these circumstances the

new, as seen from the earth, the [illegible] in the winter time from the moon. The phases of [illegible] with the ecliptic. [illegible] when the sun is at [illegible] crosses the equator [illegible] the ecliptic. Under [illegible] light in the winter [illegible] be if the moon



FIG. 68. — The moon partially illuminated by light reflected from the earth. *Photographed by Barnard at the Yerkes Observatory.*

[illegible] V and the ascending [illegible] circumstances the full



[illegible] the autumnal equinox.

[illegible] winter than it would [illegible] opposite is true when [illegible] course, the ascending somewhat illuminated by sunlight [illegible] as is shown in Fig. 68.

122. The diurnal Circles of [illegible] that the moon moves along [illegible] when the sun is on diurnal circles. Since they [illegible] equator, the full moon

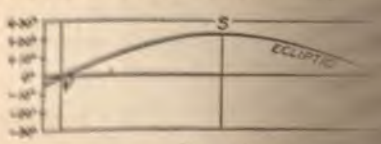


FIG. 69. — The [illegible]

[illegible] north of the equator, [illegible] is least sunlight there [illegible] least amount of moonlight [illegible] node is at the vernal [illegible] at a pole of the earth, [illegible] which is above the equator (if the motion of the [illegible] which it passes from its rising and setting is neglected). [illegible] discussion of the sun's diurnal [illegible] — One method of determining places where the moon crosses the ecliptic [illegible] by observing the difference Fig. 69, represent the celestial [illegible] points on the earth's and *VSAWV* the ecliptic. [illegible] Suppose, for simplicity, time of the year is March 21, [illegible] and that the moon

the plane of that meridian. The observer at O_1 finds the moon is the angular distance Z_1O_1M south of his zenith; and the observer at O_2 finds that it is the angular distance Z_2O_2M north of his zenith. Since the two observers know their latitudes, they know the angle O_1EO_2, and consequently, the angles EO_1O_2 and EO_2O_1. By subtracting Z_1O_1M plus EO_1O_2 and Z_2O_2M plus EO_2O_1 from 180°, the angles MO_1O_2 and MO_2O_1 are obtained. Since the size of the earth is known, the distance O_1O_2 can be found. Then, in the triangle O_1MO_2 two angles and the included side are known, and all the other parts of the triangle can be computed by trigonometry. Suppose O_1M has been found;

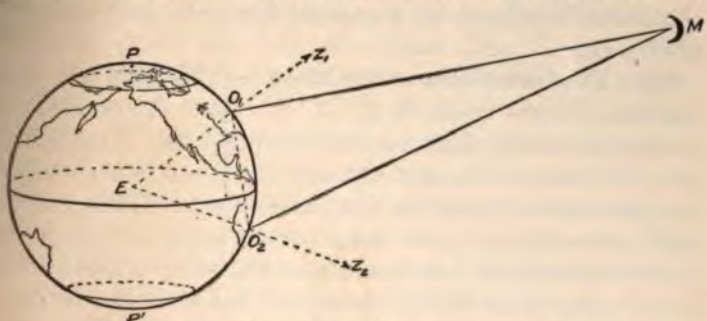


FIG. 72. — Measuring the distance to the moon.

then, in the triangle EO_1M two sides and the included angle are known, and the distance EM can be computed. In general, the relations and observations will not be so simple as those assumed here, but in no case are serious mathematical or observational difficulties encountered. It is to be noted that the result obtained is not guesswork, but that it is based on measurements, and that it is in reality given by measurements in the same sense that a distance on the surface of the earth may be obtained by measurement. The percentage of error in the determination of the moon's distance is actually much less than that in most of the ordinary distances on the surface of the earth.

full moon crosses the meridian higher
than it would if its orbit were coincide
On the other hand, in the summer time
S and the full moon is at W, the moon
farther south than it would if it were on t
these circumstances there is more moon
and less in the summer than there wou
were always on the ecliptic.

Now suppose the descending node is at
ing node is at A, Fig. 71. Under these cir

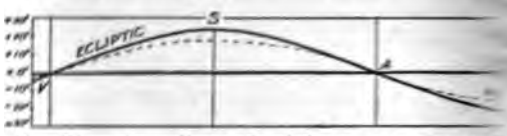


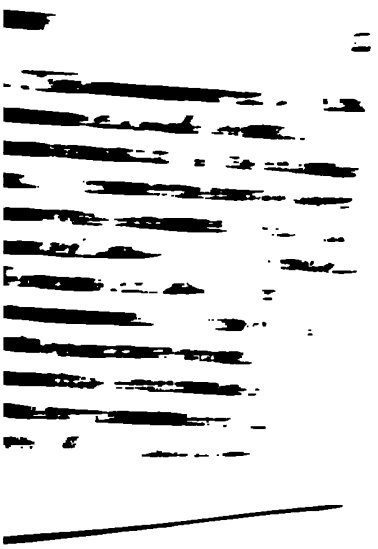
FIG. 71. — Ascending node of the moon's orbit at t

moon crosses the meridian lower in the wi
if it *moved* along the ecliptic. The opp
the sun is at S in the summer. Of cou
node of the moon's orbit might be at a
the *ecliptic*.

It is *clear* from this discussion that wh
the part of the ecliptic south of the equa
is near the part of the ecliptic which is nor
and *vice versa*. Therefore, when there is le
is most moonlight, and there is the greatest
light when the moon's ascending node
equinox. When it is continuous night at a
the gloom is partly dispelled by the moon w
horizon that half of the month in which i
first to its third quarter.

123. The Distance of the Moon. — One
mining the distance of the moon is by obse
ence in its directions as seen from two poi
surface, as O_1 and O_2 in Fig. 72. Suppo
that O_1 and O_2 are on the same meridian, a





N

on is nearer th
hen it is on h
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near the meri
us to be larger
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, and this inf

Respect to th
earth varies
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er. Its orbit i
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planets, and th
moves around
is elliptical orbi
t to the earth
f time. This
use of the pertur
the sun and pl
is nearest the ea
int is called its *ap*
h Respect to the
sun is about 40
Consequently, the
across the earth's
n around the sun
sented to scale in
ive nearness of th
l, its orbit is alwa
of the moon were
uld be when it is n
h and sun to oppo
It takes 14 days fo
sition to the latter,
e sun increases by ab

The mean distance from the center of the
center of the moon has been found to be 238,8
the circumference of its orbit is therefore 1,
On dividing the circumference by the moon's
expressed in hours, it is found that its orbital
ages 2288.8 miles per hour, or about 3357 fee

A body at the surface of the earth falls ab
first second; at the distance of the moon, w
mately 60 times the radius of the earth, it w
fall $16 \div 60^2 = 0.0044$ feet, because the ac
varies inversely as the square of the distanc
Therefore, in going 3357 feet, or nearly two
the moon deviates from a straight-line pa
of an inch.

124. The Dimensions of the Moon. — T
diameter of the moon is 31′ 5″.2. Sinc
known, its actual diameter can be compu
that the distance straight through the m
or a little greater than one fourth the dis
Since the surfaces of spheres are to each o
of their diameters, it is found that the
earth is 13.4 times that of the moon; an
of spheres are to each other as the cube
it is found that the volume of the earth
of the moon.

It has been stated that the mean a
the moon is 31′ 5″.2. The apparent d
varies both because its distance from th
varies, and also because when the moo
meridian, he is nearly 4000 miles ne
it is on his horizon. In the observati
objects the small distance of 4000 m
ciable difference in their appearance
tance from the earth to the moon is, i
240,000 miles, the radius of th
amount.

miles; but, in the meantime, the earth moves forward about 14° in its orbit from P to Q, and it, therefore, is drawn by the sun away from the straight line PT in which it was originally moving by a distance of about 3,000,000 miles.

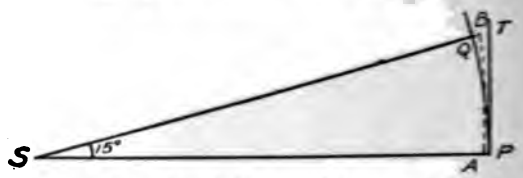


FIG. 73. — The orbit of the moon is concave to the sun.

That is, in the 14 days the moon actually moves in toward the sun away from the original line of the earth's motion 3,000,000 − 480,000 = 2,520,000 miles, and its orbit, which is represented by the broken line, is, therefore, concave toward the sun at every point.

As a matter of fact, it is the center of gravity of the earth and moon which describes what is called the earth's elliptical orbit around the sun, and the earth and moon both describe ellipses around this point as it moves on in its elliptical path around the sun. Since the earth's mass is very large compared to that of the moon, as will be seen in Art. 127, the center of the earth is always very near the center of gravity of the two bodies.

127. The Mass of the Moon. — Although the moon is comparatively near the earth, its mass cannot be obtained so easily as that of many other objects farther away.

One of the best methods of finding the mass of the moon depends upon the fact that the center of gravity of the earth and moon describes an elliptical orbit around the sun in accordance with the law of areas. Sometimes the earth is ahead of the center of gravity, and at other times behind it. When the earth is ahead of the center of gravity the sun will be seen behind the position it would apparently occupy if it were not for the moon. On the other hand

would take inconceivably great forces to make perceptible short changes in its rate of rotation. On the other hand, the moon revolves around the earth at a non-uniform rate, for it moves in such a way that the law of areas is fulfilled. Consider the moon starting from the perigee. It takes about 6.5 days, or considerably less than one quarter of its period, for the moon to revolve through 90°; and, therefore, the angle of rotation is considerably less than 90°. The result is that the part of the moon on the side toward the perigee, that is, the western edge, is brought partially into view. On the opposite side of the orbit, the eastern edge of the moon is brought partially into view. This is the libration in longitude.

In addition to this, the moon is not viewed from the earth's center. When it is on the horizon, the line from the observer to the moon makes an angle of nearly 1° (the parallax of the moon) with that from the earth's center to the moon. This enables the observer to see nearly 1° farther around its side than he could if it were on his meridian.

The result of the moon's librations is that there is only 41 per cent of its surface which is never seen, while 41 per cent is always in sight, and 18 per cent of it is sometimes visible and sometimes invisible.

130. The Density and Surface Gravity of the Moon. — The volume of the earth is about 50 times that of the moon and its mass is 81.8 times that of the moon. Therefore the density of the moon is somewhat less than that of the earth. It is found from the relative volumes and masses of the earth and moon that the density of the moon on the water standard is about 3.4.

If the radius of the moon were the same as that of the earth, gravity at its surface would be less than $\frac{1}{80}$ that at the surface of the earth; but the small radius of the moon tends to increase the attraction at its surface. If its mass were the same as that of the earth, its surface gravity would be nearly 16 times that of the earth. On taking the two

factors together, it is found that the surface gravity of the moon is about $\frac{1}{6}$ that of the earth. That is, a body on the earth weighs by spring balances about 6 times as much as it would weigh on the moon.

If a body were thrown up from the surface of the moon with a given velocity, it would ascend 6 times as high as it would if thrown up from the surface of the earth with the same velocity. Perhaps this is the reason why the forces to which both the earth and moon have been subjected have produced relatively higher elevations on the moon than on the earth. Also it would be possible for mountains of a given material to be 6 times as high on the moon as on the earth before the rock of which they are composed would be crushed at the bottom.

131. The Question of the Moon's Atmosphere. — The moon has no atmosphere, or at the most, an excessively rare one. Its absence is proved by the fact that, at the time of an eclipse of the sun, the moon's limb is perfectly dark and sharp, with no apparent distortion of the sun due to refraction. Similarly, when a star is occulted by the moon, it disappears suddenly and not somewhat gradually as it would if its light were being more and more extinguished by an atmosphere.

Besides this, if the moon had an atmosphere, its refraction would keep a star visible for a little time after it had been occulted, just as the earth's atmosphere keeps the sun visible about 2 minutes after it has actually set. In a similar way, the star would become visible a short time before the moon had passed out of line with it. The whole effect would be to make the time of occultation shorter than it would be if there were no atmosphere.

If the moon had an atmosphere of any considerable extent, there would be the effects of erosion on its surface; but so far as can be determined, there is no evidence of such action. Its surface consists of a barren waste, and it is, perhaps, much cracked up because of the extremes of heat

and cold to which it is subject. But there is nothing resembling soil except, possibly, volcanic ashes. There can be no water on the moon; for, if there were, it would be at least partly evaporated, especially in the long day, and form an atmosphere.

One cannot refrain from asking why the moon has no atmosphere. It may be that it never had any. But the evidence of great surface disturbances makes it not altogether improbable that vast quantities of vapors have been emitted from its interior. If this is true, they seem to have disappeared. There are two ways in which their disappearance can be explained. One is that they have united chemically with other elements on the moon. As a possible example of such action it may be mentioned that there are vast quantities of oxygen in the rocks of the earth's crust, which may, perhaps, have been largely derived from the atmosphere. The second explanation is that, according to the kinetic theory of gases, the moon may have lost its atmosphere by the escape of molecule after molecule from its gravitative control. This might be a relatively rapid process in the case of a body having the low velocity of escape of 1.5 miles per second (Art. 33), especially if its days were so long that its surface became highly heated.

It seems probable, therefore, that the moon could not retain an atmosphere if it had one, and that whatever gases it may ever have acquired from volcanoes or other sources were speedily lost.

132. The Light and Heat received by the Earth from the Moon. — The average distances of the earth and the moon from the sun are about the same; and, consequently, the earth and the moon receive about equal amounts of light and heat per unit area. The amount of light and heat that the earth receives from the moon depends upon how much the moon receives from the sun, what fraction it reflects, its distance from the earth, and its phase. It is easy to see that, if all the light the moon receives were reflected, the

amount which strikes the earth could be computed for any phase as, for example, when the moon is full. It is found by taking into account all the factors involved that, if the moon were a perfect mirror, it would give the earth, when it is full, about $\frac{1}{100,000}$ as much light as the earth receives from the sun. As a matter of fact, the moon is by no means a perfect reflector, and the amount of light it sends to the earth is very much less than this quantity.

It is not easy to compare moonlight with sunlight by direct measurements, and the results obtained by different observers are somewhat divergent. The measurements of Zöllner, which are commonly accepted, show that sunlight is 618,000 times greater than the light received from the full moon. Sir John Herschel's observations gave the notably smaller ratio of 465,000. At other phases the moon gives not only correspondingly less light, but less than would be expected on the basis of the part of the moon illuminated. For example, at first quarter the illuminated area is half that at full moon, but the amount of light received is less than one eighth that at full moon. This phenomenon is doubtless due to the roughness of the moon's surface. Moreover, the amount of light received from the moon near first quarter is somewhat greater than that received at the corresponding phase at third quarter, the difference being due to the dark spots on the eastern limb of the moon. On taking into consideration the whole month, the average amount of light and heat which the moon furnishes the earth cannot exceed $\frac{1}{2,500,000}$ of that received from the sun. In other terms, the earth receives as much light and heat from the sun in 13 seconds as it receives from the moon in the course of a whole year.

133. The Temperature of the Moon. — The temperature of the moon depends upon the amount of heat it receives, the amount it reflects, and its rate of radiation. About 7 per cent of the heat which falls on the moon is directly reflected, and this has no effect upon its temperature. The

and cold to which it is ... raises the tempera-
sembling soil except, possib... radiation of the moon's
no water on the moon; for ... ture is not known be-
partly evaporated, especiall... composition and physi-
atmosphere. ... determined, at least

One cannot refrain from ... of the moon.
atmosphere. It may be ... till and just before it
evidence of great surface di... shadow, as at *N*,
improbable that vast quant... is subject to the per-
from its interior. If this ... a higher temperature
appeared. There are two ... It is easy to measure
can be explained. One is ... of heat received from
with other elements on the ... what part of it is
such action it may be me... Now suppose the moon
tates of oxygen in the rocks ... that the direct rays of
perhaps, have been largely ... not received from the
The second explanation is ... recently exposed to the
theory of gases, the moon m... and from the amount
the escape of molecule afte... increases as the eclipse
control. This might be a re... approximately the
of a body having the low velo... radiation, and from
second (Art. 33), especially if ... was raised. The obser-
surface became highly heated. ... not received from the

It seems probable, therefo... the moon passes into
retain an atmosphere if it had ... that its radiation is very
it may ever have acquired fro... does not rise very
were speedily lost. ... at its maximum it

132. The Light and Heat re... points. The recent
Moon. The average distan... that the surface is
from the sun are about the ... of 200° Fahrenheit.
earth and the moon receive a... satisfactory idea
and heat per unit area. The ... the moon. It must be
the earth receives from the n... day is 28.5 times as
the moon receives from the ... second place, it has no
its distance from the earth, a... heat in the daytime
that, if all the light the mo... sky, when the sun rises

for a point on the moon, its rays continue to beat down upon the surface, which is entirely unprotected by clouds or air, for more than 14 of our days. During this time the temperature rises above the freezing point and it may even go up to the boiling point. When the sun sets, the darkness of midnight immediately follows because there is no atmosphere to produce twilight, and the heat rapidly escapes into space. In the course of an hour or two the temperature of the surface probably falls below the freezing point, and in the course of a day or two it may descend to 100° below zero. It will either remain there or descend still lower until the sun rises again 14 days after it has set.

The climatic conditions on the moon illustrate in the most striking manner the effects of the earth's atmosphere and the consequences of the earth's short period of rotation.

134. General surface Conditions on the Moon. — On the whole, the surface of the moon is extremely rough, showing no effects of weathering by air or water. It is broken by several mountain chains, by numerous isolated mountain peaks, and by more than 30,000 observed craters. There are several large, comparatively smooth and level areas, which were called *maria* (seas) by Galileo and other early observers, and the names are still retained though modern instruments show that they not only contain no water but are often rather rough. The smooth places are the areas which are relatively dark as seen with the unaided eye or through a small telescope. For example, the dark patch near the bottom of Fig. 75 and a little to the left of the center with a rather sharply defined lower edge is known as *Mare Serenitatis* (The Serene Sea). The light line running out from the right of it and just under the big crater Copernicus is the Apennine range of mountains. The most conspicuous features which are visible with an ordinary inverting telescope are shown on the map, Fig. 76.

135. The Mountains on the Moon. — There are ten ranges of mountains on the part of the moon which is visible

remaining 93 per cent is absorbed and raises the te
ture of its surface. The rate of radiation of the
surface materials for a given temperature is not kno
cause of the uncertainties of their composition and
cal condition. Nevertheless, it can be determined,
roughly, at the time of a total eclipse of the moon.

Consider the moon when it is nearly full and just b
is eclipsed by passing into the earth's shadow, as
Fig. 81. The side toward the earth is subject to t
pendicular rays of the sun and has a higher temp
than any other part of its surface. It is easy to n
with some approximation the amount of heat receive
the moon, but it is not easy to determine what part
reflected and what part is radiated. Now suppose th
passes on into the earth's shadow so that the direct
the sun are cut off. Then all the heat received fr
moon is that radiated from a surface recently expose
sun's rays. This can be measured; and, from the
received and the rate at which it decreases as the
continues, it is possible to determine approximat
rate at which the moon loses heat by radiation, an
this the temperature to which it has been raised. Th
vations show that the amount of heat received fr
moon diminishes very rapidly after the moon pass
the earth's shadow. This means that its radiation
rapid and that probably its temperature does not ri
high. It doubtless is safe to state that at its maxi
is between the freezing and the boiling points. The
work of Very leads to the conclusion that the su
heated at its highest to a temperature of 200° Fahre

It is now possible to get a more or less satisfacto
of the temperature conditions of the moon. It m
remembered, in the first place, that its day is 28.5 t
long as that of the earth. In the second place
atmospheric envelope to keep out the heat in
and to retain it at night. Consequently, when

from the earth. The mountains are often e
and lofty, in some cases attaining an altitu
20,000 feet above the plains on which they



FIG. 75. — The moon at 9¾ days. *Photographed at the Yer*

mountains on the earth were relatively as large,
be more than 15 miles high. The height of the
tains is undoubtedly due, at least in part, to the

, the mountains in its
bove its floor. On the
counted from the sea
y. For example, Pike's
evel of the ocean, which
t only about half that
it rests. The shadows
and sharp because the
are therefore well suited
objects on its surface.
remarkable and the most
pography are the craters,
en mapped. There have
mation, for new ones in
and encroached upon the
imes the newer ones are
, and sometimes they are
ewer craters have deeper
than the older, and one
t them is that very often
and spirelike peaks.
he impression to the mind
are analogous to the vol-
e is at least an immense
any lunar craters are from
a number of cases, their
demy is 115 miles across,
meter and 19,000 feet deep.
Copernicus towers 11,000
it rises. Some of these
cale that their rims would
because of the curvature of

is by no means easy, and
reached. If they are of



FIG. 77. — [illegible]

determined. [illegible] with smaller craters on its rim
of the sun in [illegible] with the 40-inch telescope
when the pi[illegible]
from these d[illegible]

volcanic origin, the activity which was present on the moon enormously surpassed anything now known on the earth. In view of the fact that there are no lava flows, and that in most cases the material around a crater would not fill it, the volcanic theory of their origin has been by no means universally accepted. Another suggestion is that the craters have been formed by the bursting out of great masses of gas which gathered under the surface of the moon and became heated and subject to great tension because of its contraction. According to this theory, the escaping gas threw out large masses of the material which covered it and thus made the rims of the craters. But it is hard to account for the mountains which are so often seen in the interiors of craters.

Gilbert suggested that the lunar craters may have been formed by the impacts of huge meteorites, in some cases many miles across. It is certain that such bodies, weighing hundreds of pounds and even tons, now fall upon the earth occasionally. It is supposed that millions of years ago the collisions of these wandering masses with the earth and moon were much more frequent than they are at the present time. When they strike the earth, their energy is largely taken up by the cushion of the earth's atmosphere; when they strike the moon, they plunge in upon its surface with a speed from 50 to 100 times that of a cannon ball. It does not seem improbable that masses many miles across and weighing millions of tons might produce splashes in the surface of the moon, even though it be solid rock, analogous to the craters which are now observed. The heat generated by the impacts would be sufficient to liquefy the materials immediately under the place where the meteorites struck, and might even cause very great explosions. The mountains in the centers might be due to a sort of reaction from the original splash, or from the heat produced by the collision. At any rate, numerous experiments with projectiles on a variety of substances have shown that pits



FIG. 78. — The great crater Clavius with smaller cr
and in its interior. *Photographed by Ritchey with the*
of the Yerkes Observatory.

like spokes from the axle of
ered with by hill or valley,
ce of several hundred miles.
proves that they are at the
ace, and they are most con-



aphed at the Yerkes Observatory (Wallace).

l moon. They are easily seen in
sed by some that they are lava
they were great cracks in the
when the craters were produced,
p with lighter colored material

The rills are cracks in the moon's surface, a mile or so wide, a quarter of a mile deep, and sometimes as much as [illegible] miles in length. They are very numerous, more than [illegible] having been so far mapped. The only things at all like them on the earth are such chasms as the Grand Canyon of the Colorado and the cut below Niagara Falls. But these gorges are the w[illegible]m, which has probably been entirely absent fro[illegible]e of the moon. At any rate, it is incredible that [illegible] have been produced by erosion. The most plausi[illegible] is that they are cracks which have been caused by [illegible] volcanic action, or by the rapid cooling and shrink[illegible]he moon.

The rays and rills are very puzzling lunar features which seem to be fundamentally unlike anything in terrestrial topography. Even our nearest neighbor thus differs very notably from the earth.

138. The Question of Changes on the Moon. — There [illegible] no well-observed changes in the larger features of the lunar topography, although, from time to time, minor alterations have been suspected. The most probable change of any important physical feature is in the small crater Linné, in Mare Serenitatis. It was mapped about a century ago, but it was said by Schmidt to be entirely invisible. It is now visible as on the original maps. It is generally believed that the differences in appearance at various times are due to slightly different conditions of illumination.

The moon's orbit is constantly shifting because of the attraction of the sun, and since the month does not contain an integral number of days, it follows that an observer [illegible] at different times exactly the same view of the moon. W. H. Pickering has noticed changes in some dark regions, depending upon the phase of the moon, which are possibly being due to some kind of vegetation in the valleys where he supposes heavier gases, such as carbon dioxide, might collect. Some of his observations have been verified by other astronomers, but

his rather bold speculations as to their meaning have not been accepted.

It is altogether probable that the moon long ago arrived at the stage where surface changes practically ceased. The only known influences which could now disturb its surface are the feeble tidal strains to which it is subject, and the extremes of temperature between night and day. While it would be too much to say that slight disintegration of the surface rocks may not still be taking place, yet it is certain that, on the whole, the moon is a body whose evolution is essentially finished. The seasonal changes are unimportant, but there is alternately for two weeks the blinding glare of the sunlight, never tempered by passing clouds or even an atmosphere, and the blackness and frigidity of the long lunar night. Month succeeds month, age after age, with no important variations in these phenomena.

139. The Effects of the Moon on the Earth. — The moon reflects a relatively small amount of sunlight and heat to the earth, and in conjunction with the sun it produces the tides. These are the only influences of the moon on the earth that can be observed by the ordinary person. It has a number of very minor effects, such as causing minute variations in the magnetic needle, the precession of the equinoxes, and slight changes in the motion of the earth; but they are all so small that they can be detected only by refined scientific methods.

There are a great many ideas popularly entertained, such as that it is more liable to rain at the time of a change of the moon, or that crops grow best when planted in certain phases, which have no scientific foundation whatever. It follows from the fact that more light and heat are received from the sun in 13 seconds than from the moon in a whole year, that its heating effects on the earth cannot be important. The passing of a fleecy cloud, or the haze of Indian summer, cuts off more heat from the sun than the moon sends to the earth in a year. Consequently, it is entirely

The rills are cr[illegible] moon has any important
wide, a quarter of [illegible]. Under this, recorded obser-
250 miles in length[illegible] rain, and the velocity
1000 having been [illegible] more than 100 years, fail
like them on the [illegible] between the weather and
gun of the Colorado [illegible]
these gorges are th[illegible] show the essential
been entirely absent [illegible] phases of the moon.
rule, it is incredibl[illegible] in a northeasterly
erosion. The most [illegible] per day, and some-
which have been [illegible] the earth. Con-
the rapid cooling a[illegible] at a certain phase
The rays and rill[illegible] few thousand miles
seem to be fundam[illegible]. The theory that a
topography. Even [illegible] moon would then
radically from the [illegible] fail of verification

138. The Questi[illegible]
have been no obser[illegible] is eclipsed when-
lunar topography, a[illegible] so that it does not
ations have been [illegible]
any natural physic[illegible]
Mare Serenitatis [illegible]
but in 1866 was [illegible]
It is now visible [illegible]
believed that the d[illegible]
have been due to st[illegible]



moon and sun.

Since the moon's [illegible] Fig. 80, *E* represents
the attraction of th[illegible], which comes to a
vals an integral num[illegible] the earth's center.
never gets at two d[illegible] within this cone is
the moon. W. H. [illegible] it by the earth's
small craters, depen[illegible] *TQP* and *SRP*
be interprets as po[illegible] cut off more and
tion which flourishe[illegible]. The shadow cone
gases, such as carb[illegible] *TQP* and *SRP*, the
observations have [illegible]

When the moon is about to be eclipsed, it passes from full illumination by the sun gradually into the penumbra, where at first only a small part of the sun is obscured, and it then proceeds steadily across the shadow of increasing density until it arrives at A, where the sun's light is entirely cut off. The distance across the earth's shadow is so great that the moon is totally eclipsed for nearly 2 hours while it is passing through the umbra, and the time from the first contact with the umbra until the last is about 3 hours and 45 minutes.

It appears from Fig. 80 that the moon would be eclipsed every time it is in opposition to the sun, but this figure is drawn to show the relations as one looks perpendicularly on the plane of the ecliptic, neglecting the inclination of the moon's orbit. Figure 81 shows another section in which



FIG. 81. — Condition in which eclipses of the moon and sun fail.

the plane of the moon's orbit, represented by MN, is perpendicular to the page. It is obvious from this that, when the moon is in the neighborhood of N, it will pass south of the earth's shadow instead of through it. The proportions in the figure are by no means true to scale, but a detailed discussion of the numbers involved shows that usually the moon will pass through opposition to the sun without encountering the earth's shadow. But when the earth is 90° in its orbit from the position shown in the figure, that is, when the earth as seen from the sun is at a node of the moon's orbit, the plane of the moon's orbit will pass through the sun, and consequently the moon will be eclipsed. At least, the moon will be eclipsed if it is full when the earth is at or near the node. The earth is at a node of the moon's orbit at two times in the year separated by an interval of six

unreasonable to sup[illegible] eclipses of the climatic effects on t[illegible] st be full when vations of temperatu[illegible] or both of the of the wind, in mu[illegible] to show with certain[illegible] e ecliptic in the phases of the moon. [illegible]0° from the sun.

The phenomena [illegible] ecliptic are the independence of the [illegible] can be an eclipse Storm centers mov[illegible] its nodes. Since direction at the rat[illegible]nce of the sun's times they can be f[illegible] earlier year after separately, if a storm[illegible] of the moon, it w[illegible] is that when they observed at quite [illegible] it has just been storm occurred at [illegible] sun gives an op- be verified for one[illegible] of determining its at all the others. [illegible] eclipse, the stars

140. Eclipses of [illegible] be observed, and over it passes int[illegible] instant at which [illegible] cuts off its light.



[illegible] known, such an exactness at the [illegible] ginable that the [illegible]. If the moon is [illegible] sun will make it [illegible] its neighborhood; receive the direc[illegible] may be exposed to the earth and [illegible]g sky will not be point at a distan[illegible] time would there The only light [illegible] revolving around that would ente[illegible] has been made, atmosphere to [illegible] the sun is para[illegible] is eclipsed when more as the [illegible] sun's light from at night in valley [illegible] diameter of the mountains. [illegible] the sun, and, con-

sequently, eclipses of the sun last for a very short time. This statement is equivalent to saying that the shadow cone of the moon comes to a point near the surface of the earth, as is shown in Fig. 80. It is also obvious from this diagram that the sun is eclipsed as seen from only a small part of the earth. As the moon moves around the earth in its orbit and the earth rotates on its axis, the shadow cone of the moon describes a streak across the earth which may be somewhat curved.

It follows from the fact that the path of the moon's shadow across the earth is very narrow, as shown in Fig. 82, that a

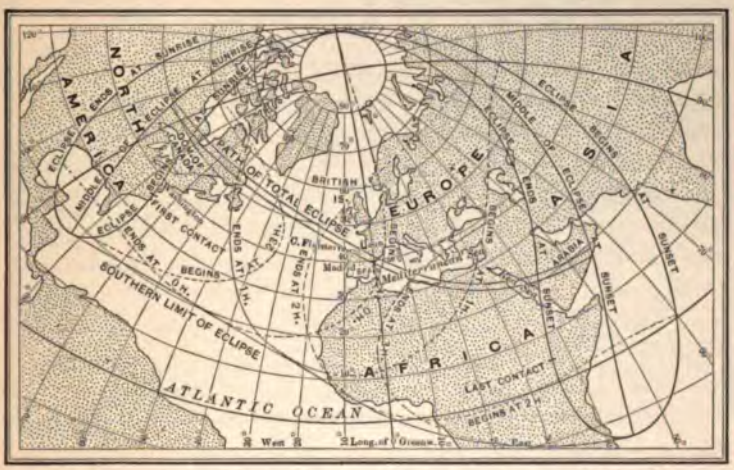


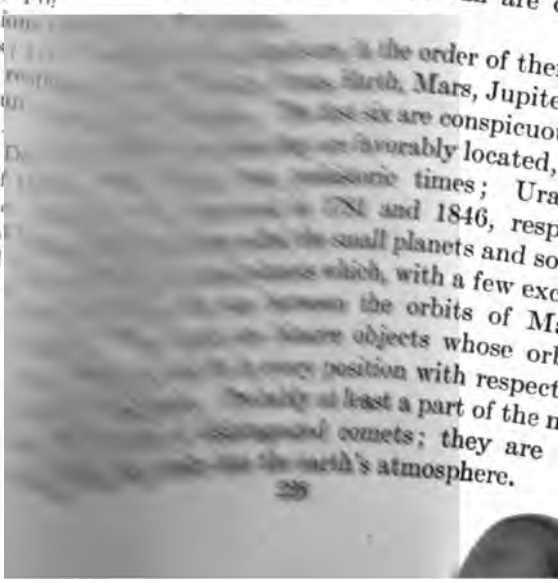
FIG. 82. — Path of the total eclipse of the sun, August 29–30, 1905.

total eclipse of the sun will be observed very infrequently at any given place. On this account, as well as because it is a startling phenomenon for the sun to become dark in the daytime, eclipses have always been very noteworthy occurrences. Repeatedly in ancient times, in which the chronology was very uncertain, writers referred to eclipses in connection with certain historical events, and astronomers, calculating back across the centuries, have been able to

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equals
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7. S





CHAPTER VIII

THE SOLAR SYSTEM

I. The Law of Gravitatio

143. The Members of the Solar System. of the solar system are the sun, the planet lites, the planetoids, the comets, and the possibly be that some of the comets and m toward the sun from great distances and are only temporary members of the sy the one preëminent body. Its volume is times that of all the other bodies combi great that it controls all their motions, and and warm them. It is impossible to t without taking into account their relati the constitution and evolution of the pendent of the planets.

The eight known planets are, in the o from the sun, Mercury, Venus, Earth, M Uranus, and Neptune. The first six are to the unaided eye when they are favora have been known from prehistorie Neptune were discovered in 1781 an The planetoids (often called the small the asteroids) are small planets which, revolve around the sun between the Jupiter. The comets are bizarre obj very elongated and lie in every positi orbits of the planets. Probably are the remains of disintegra only when they strike into th

quired for it
to the sun f
when a plan
seen from the
from opposi
compare A
be represent
and its syno
of the moon

Now retur
superior pla



FIG. 85. Fig.
sup

determined f
interval of
from E_1 and
of these two
the right an
be computed
A little co
described ari

III. *The squares of the periods of any two* *proportional to the cubes of their mean distan* *sun.*

All the complexities of the apparent motions o are explained by Kepler's three simple laws wh connection with the periods of the planets and t of their orbits.

146. The Law of Gravitation. — Newton bas est discovery, the law of gravitation, on Kepler's l each one of them he drew an important conclus

Newton proved by a suitable mathematica based on his laws of motion, that it follows fr first law that *every planet is acted on by a force rected toward the sun.* This was the first time and planets were shown to be connected dynam fore Newton's time it was generally supposed was some force acting on the planets in the direc motion which kept them going in their orbits.

The first law of Kepler led to the conclusion tha are acted on by forces directed toward the sun, information whatever regarding the manner i forces depend upon the position of the planet. law furnishes a basis for the answer to this q from it Newton proved that the *force acting on varies inversely as the square of its distance from t*

The law of the inverse squares is encounte phenomena besides gravitation. For example, magnetic and electric forces, the intensity of sound, and the magnitudes of water and earthq The reason it holds for the radiation of light is stood. The area of the spherical surface whi cross in proceeding from a point is proporti square of its radius. Since the intensity of ill inversely proportional to the illuminated area, i as the square of the distance. If gravitation depended on lines of force extending out from ma

phenomena it coördinat[es] [the] conditions were scientist of making pre[dictions] [that] began. tation in these respect[s] Newton's greatest [and] other scientific [com]petent judges. [1646–1716), a con-] [Laplace], said, "Taking [the] world to the time [was] much the better [Lagrange (1736–1813), [celestial] mechanics, wrote, [never] existed, and the [more] than once a sys- [The] English writer on the [gravitation] the law of gravita- [the] greatest scientific [and] the advance which [disclosed, or the funda- [of] truth." Compare [Leibniz] with Newton's own [words]: "I do not know [what] to myself I seem to [be] on the seashore, and [finding] a smoother pebble [while] the great ocean of [truth] There is every [reason] and unaffected ex- [pressed] the magnitude of [things] known.



[In] Newton lies buried [the] English dead, and over

Naturalis Prin[cipia] [was] engraved, "Mortals, ciples of Natur[al] [Philosophy] a man has lived for *Principia*, Nev[er] of the motions, [having found that, if explained by t[he] [action] the center of force at a

ous, then the force to which it is subject varies inversely as the square of its distance, Newton took up the converse problem. Under the assumption that the attractive force varies inversely as the square of the distance, he proved that the orbit must be what is called a *conic section*, an example of which is the ellipse.

The conic sections are highly interesting curves first studied by the ancient Greeks. They derive their name from the fact that they can be obtained by cutting a circular cone with planes. In Fig. 88 is shown a double circular cone whose vertex is at V. A plane section perpendicular to the axis of the cone gives a circle C. An oblique section gives an ellipse E; however, the plane must cut both sides of the cone. When the plane is parallel to one side, or element, of the cone, a parabola P is obtained. When the plane cuts the two branches of the double cone, the two branches of an hyperbola HH are obtained. There are in addition to these figures certain limiting cases. One is that in which the intersecting plane passes only through the vertex V giving a simple point; another is that in which the intersecting plane touches only one element of the cone, giving a single straight line; and the last is that in which the intersecting plane passes through the vertex V and cuts both branches of the cone, giving two intersecting straight lines.

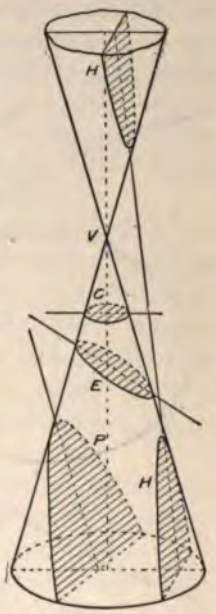


FIG. 88. — The conic sections.

The character of the conic described depends entirely upon the central force and the way in which the body is started. For example, suppose a body is started from O, Fig. 89, in the direction OT, perpendicular to OS. If the initial velocity of the body is zero, it will fall straight to

have become extinct, and, similarly, what the conditions were back before the time when life on the earth began.

The law of gravitation was undoubtedly Newton's greatest discovery, and the importance of it and his other scientific work is indicated by the statements of competent judges. The brilliant German scholar, Leibnitz (1646–1716), a contemporary of Newton and his greatest rival, said, "Taking mathematics from the beginning of the world to the time when Newton lived, what he had done was much the better half." The French mathematician, Lagrange (1736–1813), one of the greatest masters of celestial mechanics, wrote, "Newton was the greatest genius that ever existed, and the most fortunate, for we cannot find more than once a system of the world to establish." The English writer on the history of science, Whewell, said, "It [the law of gravitation] is indisputably and incomparably the greatest scientific discovery ever made, whether we look at the advance which it involved, the extent of the truth disclosed, or the fundamental and satisfactory nature of this truth." Compare these splendid and deserved eulogies with Newton's own estimate of his efforts to find the truth: "I do not know what I may appear to the world; but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, while the great ocean of truth lay all undiscovered before me." There is every reason to believe that this is the sincere and unaffected expression of a great mind which realized the magnitude of the unknown as compared to the known.

In Westminster Abbey, in London, Newton lies buried among the noblest and the greatest English dead, and over his tomb on a tablet they have justly engraved, "Mortals, congratulate yourselves that so great a man has lived for the honor of the human race."

148. The Conic Sections. — After having found that, if the orbit of a body is an ellipse with the center of force at a

focus, then the force to which it is subject varies inversely as the square of its distance, Newton took up the converse problem. Under the assumption that the attractive force varies inversely as the square of the distance, he proved that the orbit must be what is called a *conic section*, an example of which is the ellipse.



FIG. 88. — The conic sections.

The conic sections are highly interesting curves first studied by the ancient Greeks. They derive their name from the fact that they can be obtained by cutting a circular cone with planes. In Fig. 88 is shown a double circular cone whose vertex is at *V*. A plane section perpendicular to the axis of the cone gives a circle *C*. An oblique section gives an ellipse *E*; however, the plane must cut both sides of the cone. When the plane is parallel to one side, or element, of the cone, a parabola *P* is obtained. When the plane cuts the two branches of the double cone, the two branches of an hyperbola *H H* are obtained. There are in addition to these figures certain limiting cases. One is that in which the intersecting plane passes only through the vertex *V* giving a simple point; another is that in which the intersecting plane touches only one element of the cone, giving a single straight line; and the last is that in which the intersecting plane passes through the vertex *V* and cuts both branches of the cone, giving two intersecting straight lines.

The character of the conic described depends entirely upon the central force and the way in which the body is started. For example, suppose a body is started from *O*, Fig. 89, in the direction *OT*, perpendicular to *OS*. If the initial velocity of the body is *zero, it* will fall straight to

is not too great, it will describe the
will be the aphelion point. If the initial
so that the centrifugal acceler-
, the orbit will be the circle C.
is a little greater than that in the circle,
the ellipse E', and O will be the peri-
If the initial velocity is exactly $\sqrt{2}$ times



that for the circular orbit, the body will move in the parabola P. If the initial velocity is still greater, the orbit will be an hyperbola H. And finally, if the initial velocity is infinite, the path will be the straight line whose direction is OT. If the initial direction of motion is not perpendicular to OS, the results are analogous, except that there is then no initial velocity which will give a circular orbit.

It is seen from this discussion that it is as natural for a body to move in one conic
of the satellites move in orbits
the planets move in ellipses
; many comets move in
; and there may possibly
.

Laws of Force. — Many
that of the inverse squares are
the intensity of a force might
power of the distance. The char-
by a body moving subject to any
by mathematical processes.

It is found that, if the force varied according to any other power of the distance than the inverse square, except directly as the first power, then (save in special initial conditions) the orbits would be curves leading either into the center of force or out to infinity. Such a law would of course be fatal to the permanence of the planetary system.

If the force varied directly as the distance, the orbits would all be exactly ellipses, in spite of the mutual attractions of the planets, the sun would be at the center of all the orbits, and all the periods would be the same. This would imply an enormous speed for the remote bodies.

150. Perturbations. — If the planets were subject to no forces except the attraction of the sun, their orbits would be strictly ellipses. But, according to the law of gravitation, every planet attracts every other planet. Their mutual attractions are small compared to that of the sun because of their relatively small masses, but they cause sensible, though small, deviations from strict elliptical motion, which are called *perturbations*.

The mutual perturbations of the planets are sometimes regarded as blemishes on what would be otherwise a perfect system. Such a point of view is quite unjustified. Each body is subject to certain forces, and its motion is the result of its initial position and velocity and these forces. If the masses of the planets were not so small compared to that of the sun, their orbits would not even resemble ellipses.

The problems of the mutual perturbations of the planets and those of the perturbations of the moon are exceedingly difficult, and have taxed to the utmost the powers of mathematicians. In order to obtain some idea of their nature consider the case of only two planets, P_1 and P_2. The forces that P_1 and P_2 would exert upon each other if they both moved in their unperturbed elliptical orbits can be computed without excessive difficulty, and the results of these forces can be determined. But the resulting departures from elliptical motion cause corresponding alterations in the forces,

S. If ... These new perturbations ellipse ... The forces give rise to new veloci... ... to new perturbing ation ... sequence. In the solar If the ... planets are small compared the bo... ... of the series decrease helion ... masses of the planets ... that Kepler's laws would ... true, it is doubtful if ... extracted from the ... master principle of the ... small, the question ... extremely important in the ... by Lagrange and La- ... eighteenth century. They ... eccentricities, and the ... oscillate through rela- ... long time. If these re- ... system would be im- ... especially the first two ... of the planetary orbits ... other hand, the peri- ... planes of the orbits ... not only have small ... which continually change ... urbations of precisely ... precession of the equi- ... of the moon's line of

FIG. 8

sect... whi... with ... orbit ... be c...

14. ... Not only can the per- othe... ... sitions, initial motions, conc... ... given, but the converse vary... ... success. That is, if the acter... ... observations, the nature such ... be inferred. The most

celebrated example of this converse problem led to the discovery of the planet Neptune.

In 1781 William Herschel discovered the planet Uranus while carrying out his project of examining every object in the heavens within reach of his telescope. After it had been observed for some time its orbit was computed. In order to predict its position exactly it was necessary to compute the perturbations due to all known bodies. This was done by Bouvard on the basis of the mathematical theory of Laplace. But by 1820 there were unmistakable discordances between theory and observation; by 1830, they were still more serious; by 1840, they had become intolerable. This does not mean that prediction assigned the planet to one part of the sky and observation found it in a far different one; for, in 1840, its departure from its calculated position amounted to only two thirds the apparent distance between the two components of Epsilon Lyræ (Art. 88), a quantity invisible to the unaided eye. It seems incredible that so slight a discordance between theory and observation after 60 years of accumulation could have led to any valuable results.



FIG. 90. — William Herschel.

By 1820 it began to be suggested that the discrepancies in the motion of Uranus might be due to the attraction of a more remote unknown planet. The problem was to find the unknown planet. Such excessive mathematical difficul-

ties were involved that it seemed insoluble. In fact, Sir George Airy, Astronomer Royal of England, expressed himself later than 1840 as not believing the problem could be solved. However, a young Englishman, Adams, and a young Frenchman, Leverrier, with all the enthusiasm of youth, quite independently took up the problem about 1845. Adams finished his work first and communicated his results both to Challis, at Cambridge, and to Airy, at Greenwich. To say the least, they took no very active interest in the matter and allowed the search for the supposed body to be postponed. Adams continued his work and made five separate and very laborious computations. In the meantime Leverrier completed his work and sent the results to a young German astronomer, Galle. Impatiently Galle waited for the night and the stars. On the first evening after receiving Leverrier's letter, September 23, 1846, he looked for the unknown body, and found it within half a degree of the position assigned to it by Leverrier, which agreed substantially with that indicated by Adams.



FIG. 91. — John Couch Adams.



FIG. 92. — Joseph Leverrier.

Neptune is nearly three thousand millions of miles from the

earth, beyond the reach of all our senses except that of sight, and it can be seen only with telescopic aid; its distance is so great that more than four hours are required for its light to come to us, yet it is bound to the remainder of the system by the invisible bonds of gravitation. But its attraction slightly influenced the motions of Uranus, and from these slight disturbances its existence and position were inferred. Notwithstanding the fact that both Adams and Leverrier made assumptions respecting the distance of the unknown body which were somewhat in error, their work stands as a monument to the reasoning powers of the human mind, and to the perfection of the theory of the motions of the heavenly bodies.

152. The Problem of Three Bodies. — While the problem of two mutually attracting bodies presents no serious mathematical troubles, because the motion is always in some kind of a conic section, that of three bodies is one of the most formidable difficulty. It is often supposed that it has not been, and perhaps that it cannot be, solved. Such an idea is incorrect, as will now be explained.

The theory of the perturbations of the planets is really a problem of three, or rather of eight, bodies, and has been completely solved for an interval of time not too great. That is, while the orbits of the bodies cannot be described for an indefinite interval of time because they are not closed curves but wind about in a very complicated fashion, nevertheless it is possible to compute their positions with any desired degree of precision for any time not too remote. Therefore, in a perfectly real and just sense the problem has been solved.

There are particular solutions of the problem of three bodies in which the motion can be described for any period of time, however long. The first of these were discovered by Lagrange, who found two special cases. In one of them the bodies move so as to remain always in a straight line, and in the other so as to be always at the vertices of an equi-

lateral triangle. In both cases the orbits are conic
In 1878 an American astronomer, Hill, in connect
his work on the motion of the moon, discovered s
simple but immensely more important special case
1890 Poincaré, universally regarded as the greates
matician of recent times, has proved the existen
infinite number of these special cases called periodic s
In all of them the problem is exactly solved. S
recently Sundman, of Helsingfors, Finland, has i
portant mathematical sense solved the general cas
ever, in spite of all the results that have been achi
problem still presents to the mathematician unsol
tions of almost infinite variety.

153. The Cause of the Tides. — So far in th
discussion only the effect of one body on the m
another, taken as a whole, has been considered
remains to be considered the distortion of one
the attraction of another. These deformations gi
the tides.

Before proceeding to a direct discussion of the ti
lem it is necessary to state an important principle
*if two bodies are subject to equal parallel accelerat
relative positions are not changed.* The truth of th
sition follows from the laws of motion, but it is b
derstood from an illustration. Suppose two bodi
same or different dimensions are dropped from th
high tower. They have initially a certain relatio
other and they are subject to equal parallel acc
namely, those produced by the earth's attraction.
descent they fall faster and faster; but, neglecting
of the resistance of the air, they preserve the sam
to each other.

Let E, Fig. 93, represent the earth, and O a
points on its surface. Consider the tendency of
M to displace O on the surface of the earth. The
tracts the center of the earth E in the direction

matical treatment,[1] and it can be relied on to giv
all that there is in this part of the subject.

A more detailed discussion than can be entered
shows that the tide-raising forces are about 5
greater on the side of the earth which is toward
than on the side away from the moon. The forc
from the surface of the earth in the line of th
about twice as great as those which are directed
from this line. The tidal forces due to the sun
less than half as great as those due to the moon
bodies have sensible tidal effects on the earth.

154. The Masses of Celestial Bodies. — The
celestial bodies are determined from their att
other bodies. Suppose a satellite revolves arou
in an orbit of measured dimensions in an obser
From these data it is possible to compute the acc
the planet for the satellite because the attracti
the centrifugal acceleration. It is possible to
what the earth's attraction would be at the san
and, consequently, the relation of its mass to t
other planet. There has been much difficulty
the masses of Mercury and Venus because th
known satellites. Their masses have been deter
considerable reliability from their perturbatio
other and of the earth, and from their perturba
tain comets that have passed near them.

A useful formula for the sum of the masses
bodies m_1 and m_2 which attract each other acco
law of gravitation, for example, the two comp
double star, is

$$m_1 + m_2 = \frac{a^3}{P^2},$$

where a is the distance between the bodies r

[1] An analytical discussion proves that the tide-raising
tional to the product of the mass of the disturbing body an
the disturbed body, and inversely proportional to the cube
between the disturbing and disturbed bodies.

exceeding one

ance to the sun,
(Art. 123), is of
to be measured
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the two sets of data the velocity of the observer can be computed. Since the length of the year is known, the length of the earth's orbit can be obtained. Then it is an easy matter, making use of the shape of the orbit, to compute the mean distance from the earth to the sun. The results obtained in this way agree with those furnished by the direct method.

Another and closely related method depends upon the determination of the earth's motion in the line of sight (Art. 226) by means of the spectroscope. Spectroscopic technique has been so highly perfected that when stars best suited for the purpose are used the results obtained give the earth's speed with a high degree of accuracy. Its velocity and period furnish the distance to the sun, as in the method depending upon the aberration, and the results are about as accurate as those furnished by any other method.

There are several other methods for finding the distance to the sun which have been employed with more or less success. One of them depends upon transits of Venus across the sun's disk. Another involves the attraction of the sun for the moon. But none of them is so accurate as those which have been described.

157. The Elements of the Orbits of the Planets. — The position of a planet at any time depends upon the size, shape, and position of its orbit, together with the time when it was at some particular position, as the perihelion point. These quantities are called the *elements of an orbit*, and when they are given it is possible to compute the position of the planet at any time.

The size of an orbit is determined by the length of its major axis. It is an interesting and important fact that the period of revolution of a planet depends only upon the major axis of its orbit, and not upon its eccentricity or any other element. The shape of an orbit is defined by its eccentricity. The position of a planet's orbit is determined by its orientation in its plane and the relation of its plane to some standard plane of reference. The longitude of the perihelion point

defines the orientation of an orbit in its plane. The plane of reference in common use is the plane of the ecliptic. The position of the plane of the orbit is defined by the location of the line of its intersection with the plane of the ecliptic and the angle between the two planes. The distance from the vernal equinox eastward to the point where the orbit of the body crosses the ecliptic from south to north is called the longitude of the ascending node, and the angle between the plane of the ecliptic and the plane of the orbit is called the inclination.

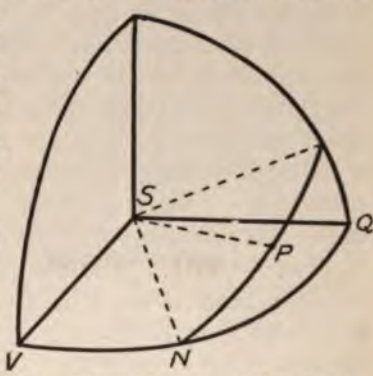


FIG. 95. — Elements of the orbit of a planet.

In Fig. 95, VNQ represents the plane of the ecliptic and SNP the plane of the orbit. The vernal equinox is at V, the angle VSN is the longitude of the ascending node, the angle $VSN + NSP$ is the longitude of the perihelion, and the angle QNP is the inclination of the orbit.

The elements of the orbits of the planets, which change very slowly, are given for January 1, 1916, in Table IV.

TABLE IV

PLANET	DISTANCE, MILLIONS OF MILES	PERIOD IN YEARS	ECCENTRICITY	INCLINATION TO ECLIPTIC	LONGITUDE OF NODE	LONGITUDE OF PERIHELION	LONGITUDE ON JAN. 1, 1916
Mercury	36.0	0.241	0.20562	7° 0′	47° 20′	76° 9′	334° 2′
Venus	67.2	0.615	0.00681	3 24	75 55	130 23	345 50
Earth	92.9	1.000	0.01674	0 00	——	101 30	99 49
Mars	141.5	1.881	0.09332	1 51	48 55	334 31	116 25
Jupiter	483.3	11.862	0.04836	1 18	99 36	12 58	3 51
Saturn	886.0	29.458	0.05583	2 30	112 55	91 24	102 20
Uranus	1781.9	84.015	0.04709	0 46	73 34	169 18	312 9
Neptune	2791.6	164.788	0.00854	1 47	130 51	43 54	120 12



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The distance of Neptune
of the earth and nearly 80
the amount of light and
a planet varies inversely as
the sun, it follows that if the
received by the earth
received by the several
Venus, 1.91; Earth, 1.00;
0.011; Uranus, 0.0027;
that the earth receives more
heat per unit area as Nep-
Mercury and Neptune the
Obviously, other things being
planets differing so greatly
enormous.

presents a smaller disk
nearest to the earth. It is
is far away in the night
like a bright star. This
sunlight received by the
light, and Neptune gets
it follows that the illu-
is nearly 700 times that of the
Another erroneous idea
is so far away from the sun
fraction of its light from other
star is more than 9000 times as
is from the sun, and, con-
than 80,000,000 times as
the sun were at the dis-

It is almost impossible to get a correct mental picture of the enormous dimensions of the solar system, and there are often misconceptions in regard to the relative dimensions of the orbits of the various planets. To assist in grasping these distances, suppose one has traveled sufficiently to have obtained some comprehension of the great size of the earth. Then he is in a position to attempt to appreciate the distance to the moon, which is so far that in spite of the fact it is more than 2000 miles in diameter, it is apparently covered by a one-cent piece held at the distance of 6.5 feet. In terms of the earth's dimensions, its distance is about 10 times the circumference of the earth. It is so remote that about 14 days would be required for sound to come from it to the earth if there were an atmosphere the whole distance to transmit it at the rate of a mile in 5 seconds.

Now consider the distance to the sun; it is 400 times that to the moon. If the earth and sun were put 4 inches apart on such a diagram as could be printed in this book, on the same scale the distance from the earth to the moon would be $\frac{1}{100}$ of an inch. If sound could come from the sun to the earth with the speed at which it travels in air, 15 years would be required for it to cross the 92,900,000 of miles between the earth and sun. Some one, having found out at what rate sensations travel along the nerve fibers from the hand to the brain, proved by calculation that if a small boy with a sufficiently long arm should reach out to the sun and burn his hand off, the sensation would not arrive at his brain so that he would be aware of his loss unless he lived to be more than 100 years of age.

The relative dimensions of the orbits of the planets can be best understood from diagrams. Unfortunately, it is not possible to represent them to scale all on the same diagram. Figure 96 shows the orbits of the first four planets, together with that of Eros, which occupies a unique position, and which has been used in getting the scale of the system. Figure 97 shows the orbits of the planets from Mars to Neptune on a

To the elements of the orbits of the [illegible] figure. The added the direction of their motion in orde[illegible] of the four complete. The result is very simple, for [illegible] the same direction, namely, eastward.

The most interesting and important el[illegible] tary orbits is the mean distance. The[illegible] from the sun is 30 times that of the [illegible] times that of Mercury. Since the [illegible] heat received per unit area by a plan[illegible] the square of its distance from the sun[illegible] units are chosen so that the amount [illegible] is unity, then the respective amounts [illegible] planets are: Mercury, 6.66; Venu[illegible] Mars, 0.43; Jupiter, 0.037; Saturn, [illegible] Neptune, 0.0011. It is seen that [illegible] than 900 times as much light and he[illegible] tune, and that in the case of Mer[illegible] ratio is more than 6000. Obvious[illegible] equal, the climatic conditions on p[illegible] in distance from the sun would be[illegible]

As seen from Neptune the sun [illegible] than Venus does to us when n[illegible] sometimes supposed that Neptun[illegible] of space where the sun looks simp[illegible] is far from the truth, for, since t[illegible] earth is 600,000 times full mo[illegible] planets. $\frac{1}{900}$ as much light as the earth[illegible] mination of Neptune by the sun[illegible] that separate the earth by the brightest full mo[illegible] frequently held is that Neptun[illegible] and Rotation Periods of that it gets a considerable fr[illegible] and Venus have no suns. The nearest known s[illegible] are subject to some undistant from Neptune as Ne[illegible] of Mercury and Venus sequently, Neptune receives [illegible] their unfavorable pomuch light and heat as it wo[illegible] stances of Uranus and tance of the nearest star.

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any markings on their surfaces. There is some ity in the diameters of the planets on account of

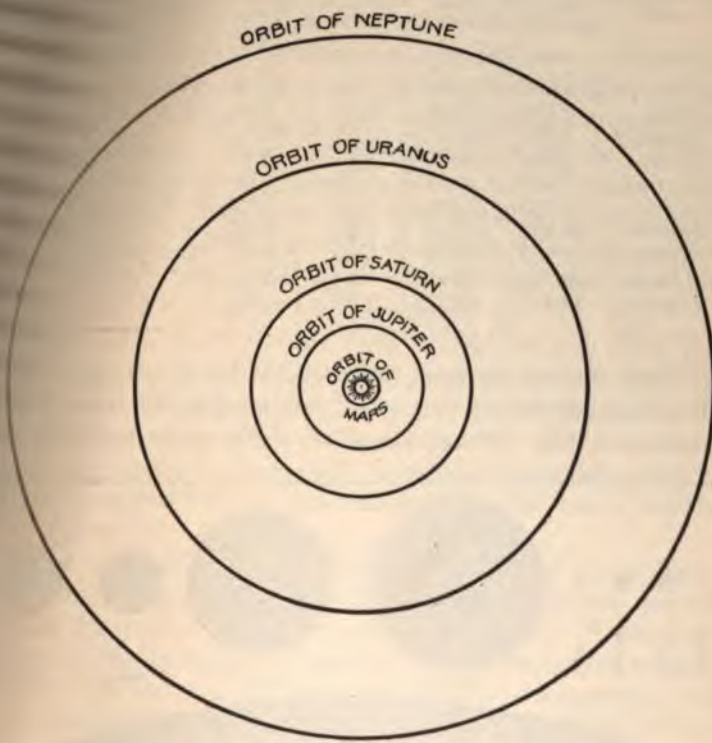


FIG. 97. — Orbit of the outer planets.

what is called irradiation, which makes a luminous object appear larger than it actually is.

The data given in Table V are based partly on Barnard's many measures at the Lick Observatory, and partly on those adopted for the American Ephemeris and Nautical Almanac.

TABLE V

BODY	MEAN DIAMETER	MASS (EARTH = 1)	DENSITY (WATER=1)	SURFACE GRAVITY ($g = 1$)	PERIOD OF ROTATION	INCLINATION OF EQUATOR TO ORBIT
Sun . .	864,392	329,390	1.40	27.64	25 d. 8 h.	7° 15′
Moon .	2,160	0.0122	3.34	0.16	27 d. 7.7 h.	6° 41′
Mercury	3,009	0.045(?)	4.48(?)	0.31(?)	?	?
Venus .	7,701	0.807(?)	4.85(?)	0.85	?	?
Earth .	7,918	1.0000	5.53	1.00	23 h. 56 m.	23° 27′
Mars .	4,339	0.1065	3.58	0.36	24 h. 37 m.	23° 59′
Jupiter .	88,392	314.50	1.25	2.52	9 h. 55 m.	3°
Saturn .	74,163	94.07	0.63	1.07	10 h. 14 m.	27°
Uranus .	30,193	14.40	1.44	0.99	?	?
Neptune	34,823	16.72	1.09	0.86	?	?

Some interesting facts are revealed by this table. The first four planets are very small compared to the outer four, and since their volumes are as the cubes of their diameters,

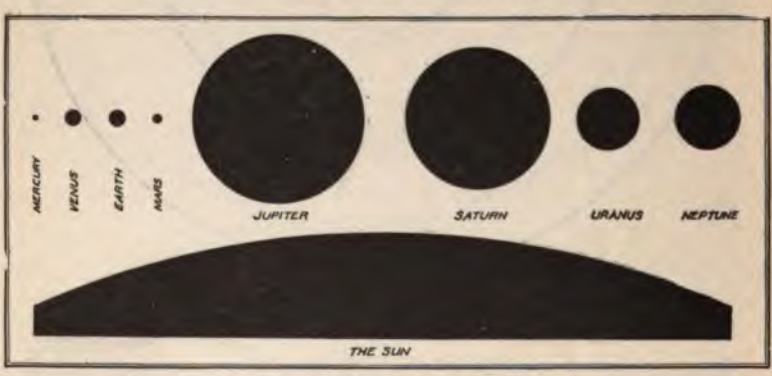


FIG. 98. — Relative dimensions of sun and planets.

the latter average more than a thousand times greater in volume than the former. The inner planets are much denser than the outer ones and, so far as known, rotate on their axes more slowly.

Figure 98 shows an arc of the sun's circumference and the

eight planets to the same scale. It is apparent from this diagram how insignificant the earth is in comparison with the larger planets, and how small they are all together in comparison with the sun.

159. The Times for Observing the Planets. — Mercury and Venus are most conveniently situated for observation when they are near their greatest elongations, for then they are not dimmed by the more brilliant rays of the sun. When they are east of the sun they can be seen in the evening, and when they are west of the sun they are observable only in the morning. Ordinarily the evening is more convenient for making observations than the morning, and therefore the results will be given only for this time.

Those planets wh ch are farther from the sun than the earth can be observed best when they are in opposition, or 180° from the sun, for then they are nearest the earth and their illuminated sides are toward the earth. When a planet is in opposition it crosses the meridian at midnight, and it can be observed late in the evening in the eastern or south-eastern sky.

The problem arises of determining at what times Mercury and Venus are at greatest eastern elongation, and at what times the other planets are in opposition. If the time at which a planet has its greatest eastern elongation is once given, the dates of all succeeding eastern elongations can be obtained by adding to the original one multiples of its synodical period. If S represents the synodical period of an inferior planet, P its sidereal period, and E the earth's period, the synodical period is given by (Arts. 120, 144)

$$\frac{1}{S} = \frac{1}{P} - \frac{1}{E};$$

and in the case of a superior planet the corresponding formula for the synodical period is

$$\frac{1}{S} = \frac{1}{E} - \frac{1}{P}.$$

On the basis of the sidereal periods given in Table IV, these

TABLE V

BODY	MEAN DIAMETER	MASS (EARTH = 1)	DENSITY (WATER=1)	SURFACE GRAVITY ($g = 1$)	PERIOD ROTATI
Sun . .	864,392	329,390	1.40	27.64	25 d. 8
Moon .	2,160	0.0122	3.34	0.16	27 d. 7
Mercury	3,009	0.045(?)	4.48(?)	0.31(?)	?
Venus .	7,701	0.807(?)	4.85(?)	0.85	?
Earth .	7,918	1.0000	5.53	1.00	23 h.
Mars .	4,339	0.1065	3.58	0.36	24 h.
Jupiter .	88,392	314.50	1.25	2.52	9 h.
Saturn .	74,163	94.07	0.63	1.07	10 h.
Uranus .	30,193	14.40	1.44	0.99	
Neptune	34,823	16.72	1.09	0.86	

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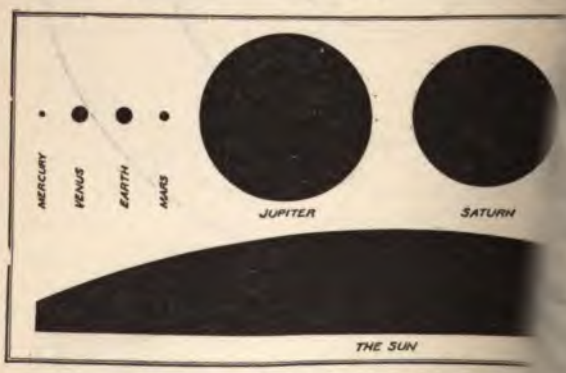


FIG. 98. — Relative dimensions of sun

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axes more slowly.

Figure 98 shows an arc of the sun's c

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n astronomers laid plans to search
ork was actually begun Piazzi, at
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ery when he noticed an object (appar-
e had previously been seen. Piazzi
which was of small dimensions, Ceres.
of Ceres had been made, but before
ached Germany by the slow processes
of those days, the philosopher Hegel
in which he claimed to have proved by

formulas, and data from… …nical reasoning that tical Almanac, the foll… …his astronomical …them.

PLANET	EASTER… TION OF…
Mercury . .	Sept.
Venus . . .	April
Mars . . .	Feb.
Jupiter . .	Oct.
Saturn . .	Jan.
Uranus . .	Aug.
Neptune . .	Jan.

…and then he was …the earth had …from which the …a little less than a …position for obser- …ing it up out of the …which it could not …almost as difficult …very. The difficulty …a young man of 24, …ns of his time, for, …blem, he devised a …ments of the orbit …. After the ele- …its position can be …d the elements of …its position led to its …

The superior pl… in opposition; the … after their greate… then relatively apr… distance more th… example, in 1916 V… April 23, but kept …

Mercury is so … …a second planetoid, its greatest elon… …2, 1804, Harding from 18° to 28° … Olbers picked up a the planet. Con… …il 1845, when Hencke very short time … …of 15 years. In 1847 for the brightest … …year since that time is somewhat bri… no difficulty in … …Wolf, of Heidelberg, Uranus and Ne… …graphy. The method bility without … …three hours with the them. Venus … …images are points, surpasses ever… …or streaks, Fig. 99, moon. Mars … …There are now …toids.

[1] In this table to… …been discovered it was ing a month.

supposed that they might be simply the fragments of an original large planet which had been torn to pieces by an explosion. If such were the case, the different parts in their orbits around the sun would all pass through the position occupied by the planet at the time of the explosion; therefore, for some time the search for new planetoids was largely confined to the regions about the points where the orbits of Ceres and Pallas intersect. But this theory of their



FIG. 99. — Photograph of stars showing a planetoid (Egeria) trail in the center of the plate. *Photographed by Parkhurst at the Yerkes Observatory.*

origin has been completely abandoned. The orbits of Eros and two other planetoids are interior to the orbit of Mars, while many are within 75,000,000 miles of this planet; on the other hand, many others are nearly 300,000,000 miles farther out, and the aphelia of four are even beyond the orbit of Jupiter. Their orbits vary in shape from almost perfect circles to elongated ellipses whose eccentricities are 0.35 to 0.40. The average eccentricity of their orbits is about 0.14, or approximately twice that of the orbits of the planets. Their inclinations to the ecliptic range all the way from zero to 35°, with an average of about 9°.

The orbits of the planetoids are distributed by no means uniformly over the belt which they occupy. Kirkwood long ago called attention to the fact that the planetoids are infrequent, or entirely lacking, at the distances at which their periods would be $\frac{1}{2}$, $\frac{1}{3}$, $\frac{2}{3}$, . . . of Jupiter's period. The numerous discoveries since the application of photography have still further emphasized the existence of these remarkable gaps. It is supposed that the perturbations by Jupiter during indefinite ages have cleared these regions of the bodies that may once have been circulating in them, but the question has not received rigorous mathematical treatment.

The diameters of Ceres, Pallas, Vesta, and Juno were measured by Barnard with the 36-inch telescope of the Lick Observatory, and he found that they are respectively 485, 304, 243, and 118 miles. There are probably a few more whose diameters exceed 100 miles, but the great majority are undoubtedly much smaller. Probably the diameters of the faintest of those which have been photographed do not exceed 5 miles.

By 1898 the known planetoids were so numerous and their orbits caused so much trouble, because of their large perturbations by Jupiter, that astronomers were on the point of neglecting them, when Witt, of Berlin, found one within the orbit of Mars, which he named Eros. At once great interest was aroused. On examining photographs which had been taken at the Harvard College Observatory in 1893, 1894, and 1896, the image of Eros was found several times, and from these positions a very accurate orbit was computed by Chandler. The mean distance of Eros from the sun is 135,500,000 miles, but its distance varies considerably because its orbit has the high eccentricity of 0.22; its inclination to the ecliptic is about 11°. At its nearest, Eros is about 13,500,000 miles from the earth, and then conditions are particularly favorable for getting the scale of the solar system (Art. 156); and at its aphelion it is 24,000,000 miles beyond the orbit of Mars (Fig. 96).

Not only is Eros remarkable because of the position of its orbit, but in February and March of 1901 it varied in brightness both extensively and rapidly. The period was 2 hr. 38 min., and at minimum its light was less than one third that at maximum. By May the variability ceased. Several suggestions were made for explaining this remarkable phenomenon, such as that the planetoid is very different in reflecting power on different parts, or that it is really composed of two bodies very near together, revolving so that the plane of their orbit at certain times passes through the earth, but the cause of this remarkable variation in brightness is as yet uncertain.

161. The Question of Undiscovered Planets. — The great planets Uranus and Neptune have been discovered in modern times, and the question arises if there may not be others at present unknown. Obviously any unknown planets must be either very small, or very near the sun, or beyond the orbit of Neptune, for otherwise they already would have been seen.

The perihelion of the orbit of Mercury moves somewhat faster than it would if this planet were acted on only by known forces. One explanation offered for this peculiarity of its motion is that it may be disturbed by the attraction of a planet whose orbit lies between it and the sun. A planet in this position would be observed only with difficulty because its elongation from the sun would always be small. Half a century ago there was considerable belief in the existence of an intra-Mercurian planet, and several times it was supposed one had been observed. But photographs have been taken of the region around the sun at all recent total eclipses, and in no case has any object within the orbit of Mercury been found. It is reasonably certain that there is no object in this region more than 20 miles in diameter.

The question of the existence of trans-Neptunian planets is even more interesting and much more difficult to answer. There is no reason to suppose that Neptune is the most re-

mote planet, and the gravitative control of the sun extends enormously beyond it. There are two lines of evidence, besides direct observations, that bear on the question. If there is a planet of considerable mass beyond the orbit of Neptune, it will in time make its presence felt by its perturbations of Neptune. Since Neptune was discovered it has made less than half a revolution, and the fact that its observed motion so far agrees with theory is not conclusive evidence against the existence of a planet beyond. In fact, there are some very slight residual errors in the theory of the motion of Uranus, and from them Todd inferred that there is probably a planet revolving at the distance of about 50 astronomical units in a period of about 350 years. The conclusion is uncertain, though it may be correct. A much more elaborate investigation has been made by Lowell, who finds that the slight discrepancies in the motion of Uranus are notably reduced by the assumption of the existence of a planet at the distance of 44 astronomical units (period 290 years) whose mass is greater than that of the earth and less than that of Neptune.

It will be seen (Art. 196) that planets sometimes capture comets and reduce their orbits so that their aphelia are near the orbits of their captors. Jupiter has a large family of comets, and Saturn and Uranus have smaller ones. As far back as 1880, Forbes, of Edinburgh, inferred from a study of the orbits of those comets whose aphelia are beyond the orbit of Neptune that there are two remote members of the solar family revolving at the distances of 100 and 300 astronomical units in the immense periods of 1000 and 5000 years. W. H. Pickering has made an extensive statistical study of the orbits of comets and infers the probable existence of three or four trans-Neptunian planets. The data are so uncertain, that the correctness of the conclusion is much in doubt.

The Zodiacal light and the Gegenschein. — The zodiacal light is a soft, hazy wedge of light stretching up

from the horizon along the ecliptic just as twilight is ending or as dawn is beginning. Its base is 20° or 30° wide and it generally can be followed 90° from the sun, and sometimes it can be seen as a narrow, very faint band 3° or 4° wide entirely around the sky. It is very difficult to decide precisely what its limits are, for it shades very gradually from an illumination perhaps a little brighter than the Milky Way into the dark sky.

The best time to observe the zodiacal light is when the ecliptic is nearly perpendicular to the horizon, for then it is less interfered with by the dense lower air. In the spring the sun is very near the vernal equinox. At this time of the year the ecliptic comes up after sunset from the western horizon north of the equator, and makes a large angle with the horizon. Consequently, the spring months are most favorable for observing the zodiacal light in the evening, and for analogous reasons the autumn months are most favorable for observing it in the morning. It cannot be seen in strong moonlight.

The *gegenschein*, or counterglow, is a very faint patch of light in the sky on the ecliptic exactly opposite to the sun. It is oval in shape, from 10° to 20° in length along the ecliptic, and about half as wide. It was first discovered by Brorsen in 1854, and later it was found independently by Backhouse and Barnard. It is so excessively faint that it has been observed by only a few people.

The cause of the gegenschein is not certainly known. It has been suggested that it is a sort of swelling in the zodiacal band which appears to be a continuation of the zodiacal light. This explanation calls for an explanation of the zodiacal light, which, of course, might well be independently asked for. The zodiacal light is almost certainly due to the reflection of light from a great number of small particles circulating around the sun in the plane of the earth's orbit, and extending a little beyond the orbit of the earth. An observer at *O*, Fig. 100, would see a considerable num-

mote planet, and the gravitative con ... on H; and enormously beyond it. There are ... gram, the zodi- besides direct observations, that be: ... extend faintly there is a planet of considerable ma: ... ed across the Neptune, it will in time make its pre: bations of Neptune. Since Neptune ... from this theory made less than half a revolution, and t ... ght why there motion so far agrees with theory is ... sation exactly against the existence of a planet beyo ... But at a point some very slight residual errors in th ... the earth, of Uranus, and from them Todd ... the apex of its probably a planet revolving at the di ... a region where, tronomical units in a period of abou ... of the combined clusion is uncertain, though it may ... arth and sun, more elaborate investigation has bee ... sort of dynamic finds that the slight discrepancies in ... circulating parti- are notably reduced by the assumpti ... caught in this a planet at the distance of 44 astrono ... to produce the years) whose mass is greater than tha ... than that of Neptune.

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162. The Zodiacal Light and the ... much fainter zodiacal light is a soft, hazy wedge o

re the variations in the distances of the planets are due to the eccentricities of their orbits?

earth and Neptune were in a line between the star; how much brighter would the star appear from the earth?

ets are all the planets similar? In what respects planets similar but different from the four outer respects are the four outer planets similar but four inner planets?

locities with which the planets move, assuming bits.

st dates at which Mercury and Venus will have rn elongations, and at which Mars, Jupiter, and pposition.

bserve the zodiacal light and describe its location

CHAPTER IX

THE PLANETS

Mercury and Venus

Mercury and Venus. — The inferior [illegible] are alike in several respects and [illegible] together. They both have [illegible] those of the moon. When [illegible] that is, at A, Fig. 101, their dark side is toward the earth and their phase is new. Since the orbits of these planets are inclined somewhat to the plane of the ecliptic, they do not in general pass across the sun's disk. If they do not make [illegible] an extremely thin crescent when they [illegible] as the sun. As they move out [illegible] these crescents increase, and their disks, [illegible] are half illuminated when they have [illegible] at B. During their motion from [illegible] to their greatest elongation at B, [illegible] conjunction at C, their distances [illegible] increase, and this increase of [illegible] extent offsets the advantage [illegible] that a larger part of their illuminated [illegible] In order that an inferior planet may be [illegible] its illuminated side be at least partly

toward the earth, but it must not be too nearly in a line with the sun. For example, a planet at *C*, Fig. 101, has its illuminated side toward the earth, but it is invisible because it is almost exactly in the same direction as the sun.

The variations in the apparent dimensions of Venus are greater than those of Mercury because, when Venus is nearest the earth, it is much nearer than the closest approach of Mercury, and when it is farthest from the earth, it is much farther than the most remote point in Mercury's orbit. At the time of inferior conjunction the distance of Venus is 25,700,000 miles, while that of Mercury is 56,900,000 miles; and at superior conjunction their respective distances are 160,100,000 and 128,900,000 miles. These numbers are modified somewhat by the eccentricities of the orbits of these three bodies, and especially by the large eccentricity of the orbit of Mercury.

Mercury and Venus transit across the sun's disk only when they pass through inferior conjunction with the sun near one of the nodes of their orbits. The sun is near the nodes of Mercury's orbit in May and November, and consequently this planet transits the sun only if it is in inferior conjunction at one of these times. Since there is no simple relation between the period of Mercury and that of the earth, the transits of Mercury do not occur very frequently. A transit of Mercury is followed by another at the same node of its orbit after an interval of 7, 13, or 46 years, according to circumstances, for these periods are respectively very nearly 22, 41, and 145 synodical revolutions of the planet. Moreover, there may be transits also when Mercury is near the other node of its orbit. The next transits of Mercury will occur on May 7, 1924, and on November 8, 1927. Mercury is so small that its transits can be observed only with a telescope.

The transits of Venus, which occur in June and December, are even more infrequent than those of Mercury. The transits of Venus occur in cycles whose intervals are, starting

[illegible] 3 years. The last two [illegible] December 8, 1874, and on [illegible] will occur on June 8, [illegible]

[illegible] the transits of Mercury and [illegible] of determining the posi- [illegible] possible to investigate [illegible] formerly used indirectly [illegible] system (Art. 156).

[illegible] of Mercury and [illegible] the ratio of the light which [illegible] The amount of light [illegible] extent upon whether or [illegible] cloud-filled atmosphere. A [illegible] and a rough and broken [illegible] while one covered [illegible] is filled with partially [illegible] reflecting power. Every [illegible] the thunderheads which [illegible] shine as white as snow [illegible] rays. It was found by [illegible] If an observer could [illegible] its brightest parts would [illegible] of its surface which are

[illegible] according to the careful work of [illegible], while that of Venus is [illegible] that the atmosphere [illegible] is entirely absent, and that

[illegible] of gases (Art. 32) and [illegible] (Art. 158, Table V) that [illegible] have sufficient gravitative con- [illegible] atmospheric envelope. This [illegible] by the fact that, when Mercury [illegible] ring is seen around it such as would

be observed if it were surrounded by any considerable atmosphere. Moreover, Müller found that the amount of light received from Mercury at its various phases proves that it is reflected from a solid, uneven surface. Therefore there is abundant justification for the conclusion that Mercury has an extremely tenuous atmosphere, or perhaps none at all.

The evidence regarding the atmosphere of Venus is just the opposite of that encountered in the case of Mercury. Its considerable mass and surface gravity, approximating those of the earth, naturally lead to the conclusion that it can retain an atmosphere comparable to our own. But the conclusions do not rest alone upon such general arguments; for, when Venus transits the sun, its disk is seen to be surrounded by an illuminated atmospheric ring. Besides this, when it is not in transit, but near inferior conjunction, the illuminated ring of its atmosphere is sometimes seen to extend considerably beyond the horns of the crescent. Also, the brilliancy of Venus decreases somewhat from the center toward the margin of its disk where the absorption of light would naturally be the greatest. Spectroscopic observations, which are as yet somewhat doubtful, point to the conclusion that the atmosphere of Venus contains water vapor. Taking all the evidence together, we are justified in the conclusion that Venus has an atmospheric envelope corresponding in extent, and possibly in composition, to that of the earth.

165. The Surface Markings and Rotation of Mercury. — The first astronomer to observe systematically and continuously the surface markings of the sun, moon, and planets was Schröter (1745–1816). He was an astronomer of rare enthusiasm and great patience, but seems sometimes to have been led by his lively imagination to erroneous conclusions.

Schröter concluded from observations of Mercury made in 1800, that the period of rotation of this planet is 24 hours and 4 minutes. This result was quite generally accepted

with a June transit, 8, 105.5, 8, and 121.5 years. The last t transits of Venus occurred on December 8, 1874, and December 6, 1882. The next two will occur on Jun 2004, and on June 5, 2012.

The chief scientific uses of the transits of Mercury Venus are that they give a means of determining the p tions of these planets, they make it possible to investi their atmospheres, and they were formerly used indire for determining the scale of the solar system (Art. 156).

164. The Albedoes and Atmospheres of Mercury Venus. — The albedo of a body is the ratio of the light w it reflects to that which it receives. The amount of l reflected depends to a considerable extent upon wheth not the body is surrounded by a cloud-filled atmosphere body which has no atmosphere and a rough and br surface, like the moon, has a low albedo, while one cov with an atmosphere, especially if it is filled with part condensed water vapor, has a higher reflecting power. E one is familiar with the fact that the thunderheads w often appear in the summer sky shine as white as when illuminated fully by the sun's rays. It was foun Abbott that their albedo is about 0.65. If an observer c see the earth from the outside, its brightest parts w undoubtedly be those portions of its surface which covered either by clouds or by snow.

The albedo of Mercury, according to the careful wo Müller, of Potsdam, is about 0.07, while that of Ve 0.60. This is presumptive evidence that the atmos of Mercury is either very thin or entirely absent, and that of Venus is abundant.

It follows from the kinetic theory of gases (Art. 32 the low surface gravity of Mercury (Art. 158, Table V Mercury probably does not have sufficient gravitativ trol to retain a very extensive atmospheric envelope. inference is confirmed by the fact that, when M transits the sun, no bright ring is seen around it such as

until after Schiaparelli took up his systematic observations of the planets, at Milan, about 1880. Schiaparelli found that Mercury could be much better seen in the daytime, when it was near the meridian, than in the evening, because the illumination of the sky was found to be a much less serious obstacle than the absorption and irregularities of refraction which were encountered when Mercury was near the horizon. His experience in this matter has been confirmed by later astronomers.

Schiaparelli came to the conclusion, from elusive and vague markings on the planet, that its axis is essentially perpendicular to the plane of its orbit, and that its periods of rotation and revolution are the same. These results are agreed to by Lowell, who has carefully observed the planet with an excellent 24-inch telescope at Flagstaff, Ariz. Although the observations are very difficult, we are perhaps entitled to conclude that the same face of Mercury is always toward the sun.

166. The Seasons of Mercury. — If the period of rotation of Mercury is the same as that of its revolution, its seasons are due entirely to its varying distance from the sun and the varying rates at which it moves in its orbit in harmony with the law of areas. The eccentricity of the orbit of Mercury is so great that at perihelion its distance from the sun is only two thirds of that at aphelion. Since the amount of light and heat the planet receives varies inversely as the square of its distance from the sun, it follows that the illumination of Mercury at aphelion is only four ninths of that at perihelion. It is obvious that this factor alone would make an important seasonal change.

Whatever the period of rotation of Mercury may be, its rate of rotation must be essentially uniform. Since it moves in its orbit so as to fulfill the law of areas, its motion of revolution is sometimes faster and sometimes slower than the average. The result of this is that not exactly the same side of Mercury is always toward the sun, *even if its periods*



to that of its orbit is 53°. These results were generally accepted until 1880, when Schiaparelli announced that Venus, like Mercury, always has the same face toward the sun.

The observations of Schiaparelli were verified by himself in 1895, and they have been more or less definitely confirmed by Perrotin, Tacchini, Mascari, Cerulli, Lowell, and others. However, it must be remarked that the atmosphere interferes with seeing the surface of Venus and that the observations are very doubtful. Moreover, recent direct observations by a number of experienced astronomers point to a period of rotation of about 23 or 24 hours.

The spectroscope can also be applied under favorable conditions to determine the rate at which a body rotates. In 1900 Bélopolsky concluded from observations of this sort that the period of rotation of Venus is short. More accurate observations by Slipher, at the Lowell Observatory, show no evidence of a short period of rotation. The preponderance of evidence seems to be in favor of the long period of rotation, but the conclusion is at present very uncertain.

168. The Seasons of Venus. — The character of the seasons of Venus depends very much upon whether the planet's period of rotation is approximately 24 hours or is equal to its period of revolution. If the planet rotates in the shorter period and if its equator is somewhat inclined to the plane of its orbit, the seasons must be quite similar to those of the earth, though the temperature is probably somewhat higher because the planet is nearer to the sun. On the other hand, if the same face of Venus is always toward the sun, the conditions must be more like those on Mercury, though the range of temperatures cannot be so extreme because its atmosphere reduces the temperature on the side toward the sun and raises it on the opposite side by carrying heat from the warmer side to the cooler.

Suppose the periods of rotation and revolution of Venus are equal. Since the orbit of Venus is very nearly circular, it is subject to only a small libration and only a very narrow zone

around it has alternately day and night. The position of the sun in its sky is nearly fixed and the climate at every place on its surface is remarkably uniform. There must be a system of atmospheric currents of a regularity not known on the earth, and it has been suggested that all the water on the planet was long ago carried to the dark side in clouds and precipitated there as snow. This conclusion is not necessarily true, for it seems likely that the air would ascend on the heated side and lose its moisture by precipitation before the high currents which would go to the dark side had proceeded far on their way.

Considered as a whole, Venus is more like the earth than any other planet; and, so far as can be determined, it is in a condition in which life can flourish. In fact, if any other planet than the earth is inhabited, that one is probably Venus. It must be added, however, that there is no direct evidence whatever to support the supposition that there is life upon its surface.

II. Mars

169. The Satellites of Mars. — In August, 1877, Asaph Hall, at Washington, discovered two very small satellites revolving eastward around Mars, sensibly in the plane of its equator. They are so minute and so near the bright planet that they can be seen only with a large telescope, and usually it is advantageous, when observing them, to obscure Mars by a small screen placed in the focal plane. These satellites are called Phobos and Deimos. The only way of determining their dimensions is from the amount of light they reflect to the earth. Though Phobos is considerably brighter than Deimos, its diameter probably does not exceed 10 miles.

Not only are the satellites of Mars very small, but in other respects they present only a rough analogy to the moon revolving around the earth. The distance of Phobos from the center of Mars is only 5850 miles, while that of Deimos is 14,650 miles. That is, Phobos is only 3680 miles from the

surface of the planet. The curvature of the planet's surface is such that Phobos could not be seen by an observer from latitudes greater than 68° 15′ north or south of the planet's equator. The relative dimensions of Mars and the orbits of its satellites are shown in Fig. 102.

As was seen in Art. 154, the period of a satellite depends upon the mass of the planet around which it revolves and upon its distance from the planet's center. Notwithstanding the small mass of Mars, its satellites are so close that their periods of revolution are very short, the period of Phobos being 7 hrs. 39 m. and that of Deimos being 30 hrs. 18 m. Since Mars rotates on its axis in 24 hrs. and 37 m., Phobos makes more than 3 revolutions while Mars is making one rotation. It therefore rises in the west, passes eastward across the sky, and sets in the east. Here is an example in which the direction of apparent motion and actual motion are the same. The period of Phobos from meridian to meridian is 11 hrs. and 7 m. On the other hand, Deimos rises in the east and sets in the west with a period from meridian to meridian of 131 hrs. and 14 m.



FIG. 102. — Mars and the orbits of its satellites.

170. The Rotation of Mars. — In 1666 Hooke, an English observer, and Cassini, at Paris, saw dark streaks on the ruddy disk of Mars, and these features of the planet's surface are so definite and permanent that even to-day astronomers can recognize the objects which these men observed and drew. Some of them are shown in Fig. 103, which is a

series of 9 photographs, taken one after the other at short intervals, by Barnard, at the Yerkes Observatory. By comparing observations at one time with those made at a later date the period of rotation of the planet can be found. In fact, considerable rotation is observable in the short interval covered by the photographs in Fig. 103. Hooke

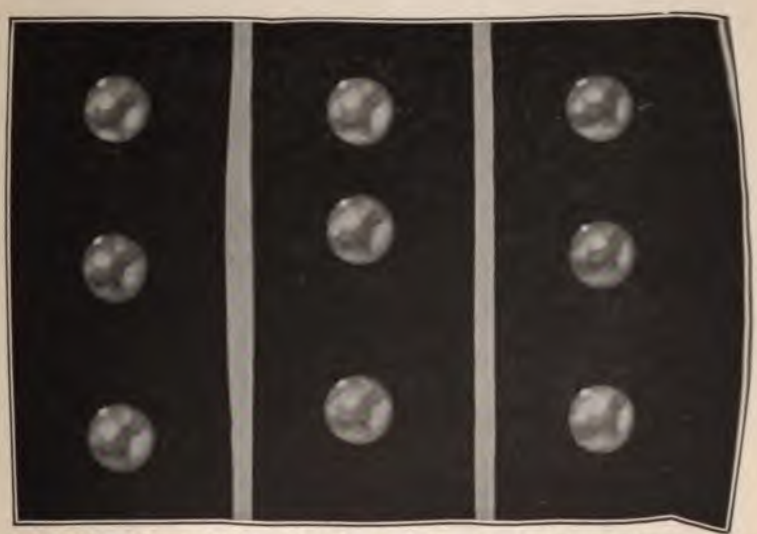


FIG. 103.—Mars. *Photographed by Barnard with the 40-inch telescope of the Yerkes Observatory, Sept. 28, 1909.*

and Cassini soon discovered that Mars turns on its axis in a period of a little more than 24 hrs. By comparing their observations with those of the present day it is found that its period of rotation is 24 hrs. 37 m. 22.7 secs. The high order of accuracy of this result is a consequence of the fact that the importance of the errors of the observations diminishes as the time over which they extend increases.

The inclination of the plane of the equator of Mars to the plane of its orbit is between 23° and 24°. The inclination cannot be determined as accurately as the period of

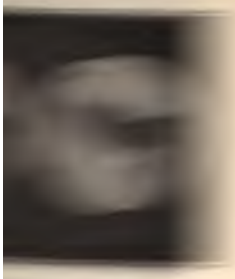
rotation because the only advantage
observations consists in their number.
uncertainty, the obliquity of the ecli
equator is certainly approximately e
earth, and, consequently, the seasonal
tatively much like those of the ear
difference is that the period of Mars i
and, therefore, while its day is only a li
of the earth, its year is nearly twice as lo
to imply by these statements that the
similar to that of the earth. Its distan
so much greater that the amount of light
per unit area is only about 0.43 of th
receives.

171. The Albedo and Atmosphere of
to the observations of Müller, the albe
which indicates probably a thin atmosph

The surface gravity of Mars is only 0.3
and, consequently, it would be expected
kinetic theory of gases that it might retai
though not a very extensive one. Dire
the planet confirm this conclusion. In
surface can nearly always be seen withou
ference from atmospheric phenomena.
seen from a distant planet, such as Ven
the clouds now and then entirely shut o
view, but the reflection and absorption
where there were no clouds would probab
sible to see distinctly anything on its su

The fact that Mars has a rare atmosph
by the suddenness with which it cuts
stars when it passes between them and
planets which have extensive atmosphere
extinguish the light from the stars more
atmosphere of Mars, relatively to its mass
density as that of the earth, it would be r

nd the south pole of Mars has been
lied than the one at the north pole
e is turned toward the earth when Mars
the perihelion point of its orbit. The
bit of this planet is so great that its
t of the earth when it is at its perihelion
helion of the earth's orbit) is more than
than when it is at its aphelion. How-
immense time the mutual perturbations
change the orbit of Mars that its north-
be more favorably situated for observa-
than its southern.



f Mars are due to snow, there must be
atmosphere. The spectroscope is an
nder suitable conditions enables the
mine the constitution of the atmosphere
from which he receives light. Mars is
the purpose because, in the first place,
rom it is only reflected sunlight which
more or less of its shallow and tenuous
n the second place, the atmosphere of
tains usually a large amount of water
sy to make sure that the absorption
225) may not be due altogether to the
arth's atmosphere.

roscopic investigations of Huggins and
rd the existence of water on Mars; the
nd Campbell, with much more powerful
der better atmospheric conditions, gave
but the spectograms obtained by Slipher
rvatory, under exceptionally favorable
limatic conditions, again indicate water
of the difficulties of the problem, a nega-
arcely be regarded as being conclusive
ntire absence of water on Mars, while
amount of water vapor in its atmosphere

diminishes in size, contracting first around the edges; it then breaks up more or less, and it sometimes entirely disappears in the late summer.

After the southern polar cap has shrunk to the dimensions given by Barnard's observation of August 13, 1894, Fig. 105, an elongated white patch is found to be left behind the retreating white sheet. The same thing was observed in the same place at the corresponding Martian season in 1892, and also at later oppositions. This means that the phenomenon is not an accident, but that it depends upon the nature of the surface of Mars. Barnard has suggested that there may be an elevated region in the place on which the spot is observed where the snow or frost remains until after it has entirely disappeared in the valleys. At any rate, this phenomenon strongly points to the conclusion that there are considerable irregularities in the surface of Mars, though on the whole it is probably much smoother than the earth. This is an important point which must be borne in mind in interpreting other things observed upon the surface of the planet.



FIG. 105. — Disappearance of polar cap of Mars (Barnard).



is not unreasonable and
nomena of its polar cap
The distance of Mars
receives only about 0.43
area as is received by
how its polar caps can
the poles of the earth
snow. The response
many of them ignoring
on which a correct an
In the first place
what the average tem
phere and surface
earth. That is, let
would be if its dist
Mars. The amount
the average equals
temperature would
fore, the amount of
the average 0.43
Now the amount
character of its
calculation the
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fied both theore
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bodies are as
Now apply
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491° below
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absolute tem

snow evapo-
On the other
nce of water
er its tempera-
t at the freezing
the water vapor
and evapora-
and if it is scarce,
low the freezing
processes begin
present and not
the remainder of
aporates (or sub-
sity of the water
pressure is less than
; or, if this is the
re falls below −35°,
evaporates at 80°
above it is less than
with this pressure of
the temperature falls
earth's atmosphere on
than it is in the summer.
Suppose its polar
frost, as they appear
ly or entirely disappear in
that the atmosphere is dry
place at the temperature
If the temperature of Mars
water vapor in its atmosphere
remains of the polar caps; and
of water vapor in the atmosphere
could be computed.
the possible temperature
and reference has been made to

the possibility of determining the water content of its atmosphere by means of the spectroscope. There is an additional line of evidence which bears on the question in hand. The surface of the planet is largely of a brick-red color, and is interpreted as being in a desert condition. While there are dark regions which have been supposed possibly to be marshes, there are certainly no large bodies of water on its surface comparable to the oceans and seas upon the earth. These things confirm the conclusion that water is not abundant on Mars and that its mean temperature may be below zero; but, in the equatorial regions in the long summers, the temperature may rise for a considerable time even above the freezing point.

173. The Canals of Mars. — In 1877, Schiaparelli, an Italian observer of Milan, made the first of a series of important discoveries respecting the surface markings of Mars. Although he had only a modest telescope of 8.75 inches' aperture, he found that the brick-red regions, which had been supposed to be continental areas, were crossed and recrossed by many straight, dark, greenish streaks which always ended in the darker regions known as "seas." These streaks were of great length, extending in uniform width from a few hundred miles up to three or four thousand miles. While they appeared to be very narrow, they must have been at least 20 miles across. Schiaparelli called them "canali" (channels), which was translated as "canals," a designation unfortunately too suggestive, for they have no analogy to anything on the earth. When a number of them intersect, there is generally a dark spot at the point of intersection which is called a "lake." Sometimes a number of them intersect at a single point; and, according to Lowell, the junctions of canals are always surrounded by lakes, while lakes are found at no other places.

In the winter of 1881–82 Mars was again in opposition, though not so near the earth as in 1877. Schiaparelli not only verified his earlier observations, but he also found the

le water vapor in the air surrounding it, the snow evapo-
es into water vapor without first melting. On the other
nd, if the atmosphere contains an abundance of water
por, the snow does not evaporate until after its tempera-
e has risen above the freezing point. But at the freezing
int the snow turns into water.

The gist of the whole matter is this: If the water vapor
the atmosphere is abundant, precipitation and evapora-
n take place above the freezing point; and if it is scarce,
cipitation and evaporation take place below the freezing
int. The temperature at which these processes begin
pends only on the density of water vapor present and not
all upon the constitution and density of the remainder of
atmosphere. For example, snow evaporates (or sub-
nes) at −35° Fahrenheit when the density of the water
por surrounding it is such that its pressure is less than
0018 of ordinary atmospheric pressure; or, if this is the
ter-vapor pressure and the temperature falls below −35°,
ow is precipitated. Similarly, water evaporates at 80°
hrenheit if the pressure of the water above it is less than
34 of atmospheric pressure; or, with this pressure of
ter vapor, precipitation occurs if the temperature falls
low 80°. This explains why the earth's atmosphere on
e whole is much dryer in the winter than it is in the summer.

The application to Mars is simple. Suppose its polar
ps are actually due to snow or hoar frost, as they appear
be. The fact that they nearly or entirely disappear in
e long summers means only that the atmosphere is dry
ough for evaporation to take place at the temperature
ich prevails on the planet. If the temperature of Mars
re known, the amount of water vapor in its atmosphere
uld be computed from the phenomena of the polar caps; and
nversely, if the amount of water vapor in the atmosphere
Mars were known, its temperature could be computed.

Some direct considerations on the possible temperature
Mars have been given, and reference has been made to

the possibility of determining the water content of its atmosphere by means of the spectroscope. There is an additional line of evidence which bears on the question in hand. The surface of the planet is largely of a brick-red colour, and is interpreted as being in a desert condition. While there are dark regions which have been supposed possibly to be marshes, there are certainly no large bodies of water like its surface comparable to the oceans and seas upon the earth. These things confirm the conclusion that water is not abundant on Mars and that its mean temperature is far below zero; but, in the equatorial regions in the long summer, the temperature may rise for a considerable time above the freezing point.

III. The Canals of Mars.—In 1877, Schiaparelli, Italian observer of Milan, made the first of a series of important discoveries respecting the surface markings of Mars. Although he had only a modest telescope of 8.75 inches aperture, he found that the brick-red regions, which he supposed to be continental areas, were crossed and recrossed by many straight, dark, greenish streaks which he ranked in the darker regions known as "seas." These streaks were of great length, extending in millions with a few hundred miles up to three or four thousand miles, and they appeared to be very narrow, they never being more than at least 20 miles wide. Schiaparelli called these streaks "canali" (channels), which was translated as "canals," a term which unfortunately has suggested, for many persons, the existence of anything in the work. When a number of canals meet, there is generally a dark spot at the point of junction, which is called a "lake." Sometimes a number of canals intersect at a single point, and sometimes the canals at the junctions of seas are always accompanied by lakes. Similar lakes are found on other planets.

In the winter of 1881–82 Mars was again favourably placed, though not so near the earth as in 1877. Schiaparelli only verified his earlier observations, but he also

remarkable fact that a number of the canals had d
that is, that, in a number of cases, two canals ran
to each other at a distance of from 200 to 400 miles, s
on Lowell's map in Fig. 106, which is a photogra
globe on which he had drawn all the markings
observed. The doubling was found to depend upon

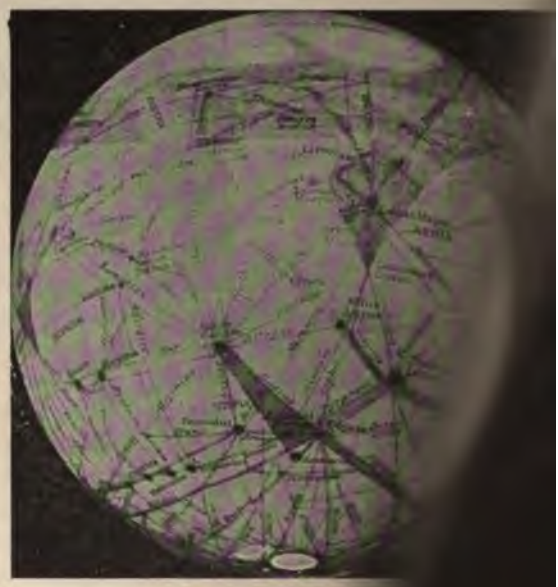


FIG. 106. — Lowell's map

sons and to develop with great rapi
at the Martian equinox.

The history of the observations
since the time of Schiaparelli is fill
able contradictions. The obser
Italian have been confirmed by
mers, among whom may be men
of Nice, Williams, of England,
and especially Lowell, who

III. Jupiter

...iter's Satellite System. — The first objects dis... Galileo when he pointed his little telescope to ... 1610 were the four brightest moons of Jupiter. ...barely beyond the limits of visibility without optical ...indeed, could be seen with the unaided eye if they ...obscured by the dazzling rays of Jupiter. No other ...of Jupiter was discovered until 1892, when Barnard, ...the Lick Observatory, caught a glimpse of a fifth ...ry close to the planet. It is so small and so buried ... rays of the neighboring brilliant planet that it can ...n only by experienced observers with the aid of the ... powerful telescopes in the world.

...rly in 1905 Perrine found by photography that Jupiter ... still two more satellites which are more remote from the ...net than those previously known. Their distances from ...piter are both about 7,000,000 miles and their periods of ...volution are about 0.75 of a year. The eccentricities of ...heir orbits are considerable and their paths actually loop ...through one another. The mutual inclination of their ...orbits is 28° and they do not pass nearer than 2,000,000 ...miles of each other.

The seven satellites so far enumerated revolve around Jupiter from west to east, but two more have been discovered whose motion is in the opposite direction. The eighth was found by Melotte, at Greenwich, England, in January, 1908. It revolves around Jupiter at a mean distance of approximately 14,000,000 miles in a period of about 740 days. Its orbit is inclined to Jupiter's equator by about 28°. The ninth was discovered by S. B. Nicholson, in July, 1914, at the Lick Observatory. Its mean distance from Jupiter is about 15,400,000 miles and its period is nearly 3 years. These remote satellites are very small and faint, the ninth being of the nineteenth magnitude, and the eighth about one magnitude brighter.

is less than on the earth, the light and heat rec
the sun are less and the temperature is probably
the atmosphere is much less abundant, and it ma
different in constitution, and the seasonal ch
nearly twice as long. The plants and animals
habit the earth are more or less perfectly adap
conditions existing on its surface, and the condi
not been made to fit them, as was once generall
Similarly, life on other planets must be adapt
environment in which it is placed or it would sho

Further, if Mars or any other world is inhabit
no reason to suppose that its highest intelligence h
the precise stage attained by the human race.
intelligent creatures on another planet may be in
tion corresponding to that in which our ancestors
they lived in caves and ate uncooked food; or,
years ago they may have passed through the sta
and deadly competition in which the human rac

It is a curious fact that those who know but l
astronomy are nearly always very much interes
question whether other worlds are inhabited, whi
astronomers who devote their whole lives to
scarcely give the question of the habitability of o
a thought. Astronomers are doubtless influen
knowledge that such speculations can scarcely
tainty, and they are deeply impressed by the
laws which they find operating in the universe. N
there seems to be no good reason why we sho
and then consider the question of the existence
only on the other planets of the solar system, bu
millions of planets that possibly circulate aroun
Such speculations help to enlarge our mental
to give us a better perspective in contemplati
and destiny of the human race, but we should
that they are speculations.

The first four satellites discovered are numbered I, II, III, IV in the order of their distance from Jupiter. The fifth, although it is very close to Jupiter, was given the number V. The orbits of these five satellites, shown in Fig. 109, are nearly circular and lie in the plane of Jupiter's equator. The four larger satellites are of considerable dimensions and their diameters have been determined by Barnard, the results being given in the following table:

TABLE VII

SATELLITE	DISTANCE FROM CENTER OF JUPITER	PERIOD OF REVOLUTION	DIAMETER
V (Unnamed) .	112,500 mi.	0d. 11h. 57m.	about 100 mi.
I (Io) . . .	261,000 mi.	1d. 18h. 28m.	2452 mi.
II (Europa) .	415,000 mi.	3d. 13h. 14m.	2045 mi.
III (Ganymede)	664,000 mi.	7d. 3h. 43m.	3558 mi
IV (Callisto) .	1,167,000 mi.	16d. 16h. 32m.	3345 mi.
VI (Unnamed) .	7,300,000 mi.	about 266 days	small
VII (Unnamed) .	7,500,000 mi.	about 277 days	small
VIII (Unnamed) .	14,000,000 ± mi.	about 740 days	very small
IX (Unnamed) .	15,400,000 ± mi.	nearly 3 years	very small

176. Markings on Jupiter's Satellites. — The great distance of Jupiter makes it difficult to detect any but large and distinctly colored markings on its satellites. In 1890 Barnard found satellite I to be elongated parallel to the equator of Jupiter when transiting its darker portions and elongated, or double, in the opposite direction when passing over its brighter parts. He interpreted this as meaning that the poles of the satellite are dark and that the equatorial belt is light colored. The accompanying drawing, Fig. 110 showing the satellite transiting a light region above and dark one below, exhibits the observed appearance at th left and the probable actual condition at the right. Whe held at some distance from the eye, the two appear th same.

Discovery of

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FIG. 111. — Discovery of velocity

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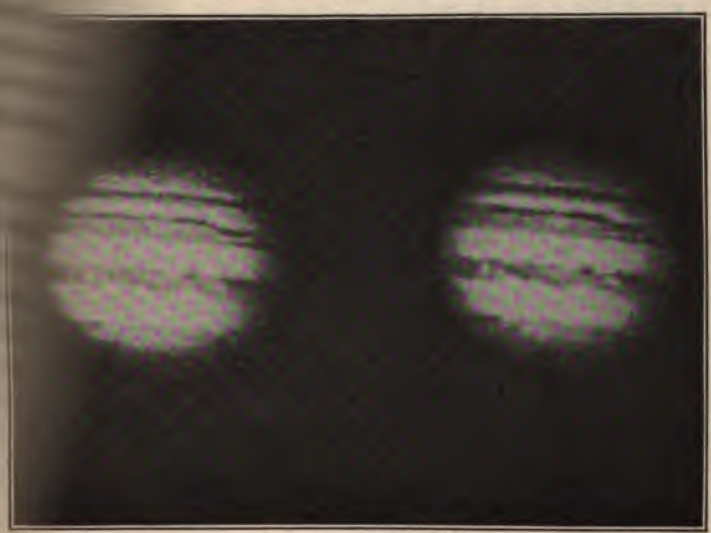


FIG. 113. — Photographs of Jupiter (E. C. Slipher, Lowell Observatory).

composed seems to be sinking back beneath the vapors which surround the planet.

A very remarkable thing in connection with the red spot was that its period of rotation increased 7 seconds the first eight years following its discovery, but it has remained essentially constant since that time. Possibly the increase in period of rotation of the red spot, which was somewhat longer than that of the surrounding material which continually flowed by it, was due to its being elevated so that its distance from the axis of rotation of the planet was increased. Under these conditions the rate of rotation would be reduced

TABLE IX

Equatorial radius of Saturn	38,235 miles
Center of Saturn to inner edge of crape ring . .	44,100 miles
Center of Saturn to inner edge of bright ring . .	55,000 miles
Center of Saturn to outer edge of bright ring . .	73,000 miles
Center of Saturn to inner edge of outer ring . .	75,240 miles
Center of Saturn to outer edge of outer ring . .	86,300 miles

The distance from the surface of Saturn to the inner edge of the thin, faint ring, known as " the crape ring," is nearly 6000 miles. The width of the crape ring is about 11,000 miles. Outside of the crape ring is the main bright ring, whose width is about 18,000 miles. Its brightness increases

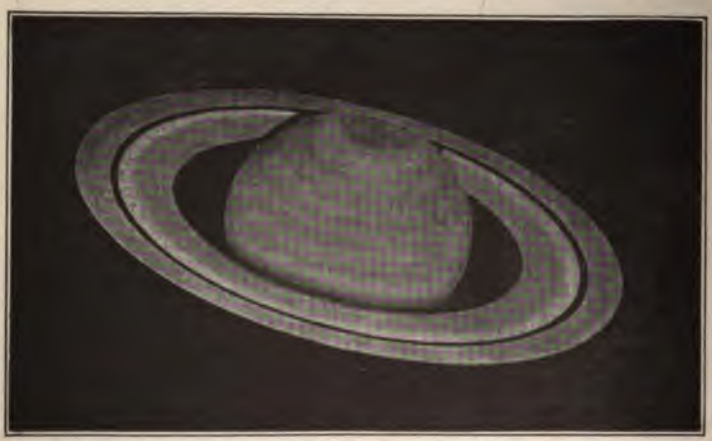


FIG. 116. — Saturn with rings tilted at greatest angle (drawing by Barnard).

from its junction with the crape ring outward nearly to its outer margin. At its brightest place it is as luminous as the planet itself. Beyond the main bright ring there is a dark gap about 2200 miles across. It is known as " Cassini's Division " because it was first o[illegible]v Cassini. Outside of this dark space is the oute[illegible]g with a width of

about 11,000 miles. The distance across the whole ring system from one side to the other is about 172,600 miles.

The rings of Saturn are inclined about 27° to the plane of the planet's orbit and about 28° to the plane of the ecliptic. Consequently, they are observed from the earth at a great variety of angles. When their inclination is high, Saturn and its ring system present through a good telescope one of the finest sights in the heavens, as is evident from Figs.



FIG. 117. — Saturn. *Photographed Nov. 19, 1911, with the 60-inch telescope of the Mount Wilson Solar Observatory.*

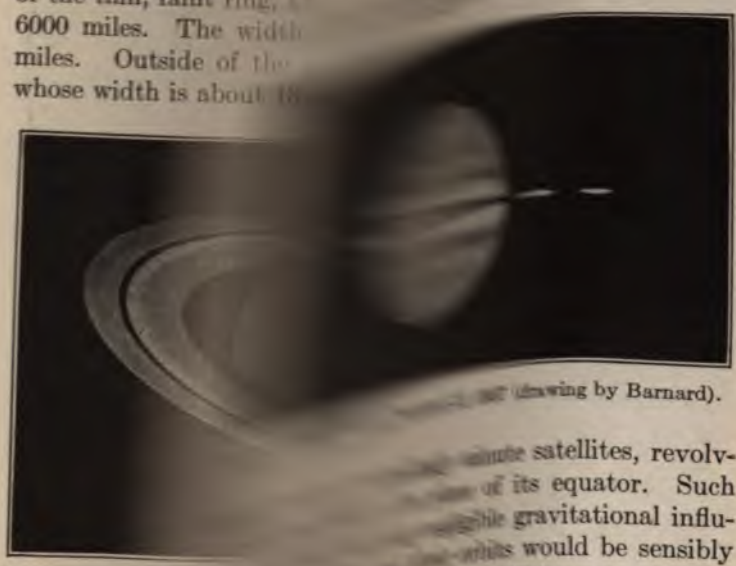
116 and 117. When their plane passes through the earth, they appear to be a very thin line and even entirely disappear from view for a few hours, as Barnard found when observing them with the great 40-inch telescope in 1907. It follows that the rings must be very thin, their thickness probably not exceeding 50 miles. When the rings were nearly edgewise to the earth, Barnard could see them faintly; but the places which are entirely vacant when they are highly inclined to the earth, were found to be brighter than the places where the rings are really brilliant (Fig. 118). Barnard

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183. The Constitution of Saturn's Rings. The rings of Saturn have the same appearance
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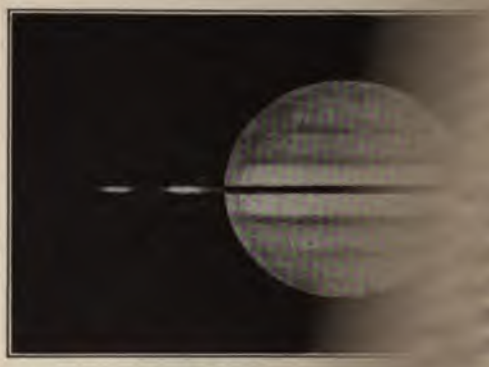


FIG. 118. — Rings of Saturn, Decemb

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the axis of Jupiter is almost exactly perpendicular to the plane of its orbit.

186. The Physical Condition and Seasonal Changes of Saturn. — The density of Saturn is about 0.63 on the water standard. Consequently, it must be largely in a gaseous condition. Probably no considerable portion of it is purely gaseous, for it seems more likely, in view of the fact that it is opaque, that the gases of which it is composed are filled with minute liquid particles, just as our own atmosphere becomes charged with globules of water, forming clouds.

The remarkable relative motions of the different parts of the surface of Saturn show that it is at least in a fluid state and that it is a place of the wildest turmoil. Doubtless it is a world whose evolution has not yet sufficiently advanced to give it any permanent markings, much less to fit it as a place in any way suitable for the abode of even the lowest forms of life.

The high inclination of the plane of Saturn's equator to that of its orbit gives it marked seasonal changes. Moreover, its orbit is rather more eccentric than the orbits of the other large planets. But it is so far from the sun that it receives only $\frac{1}{90}$ as much light and heat per unit area as the earth receives; and it follows that its surface is very cold unless it has an atmosphere of remarkable properties, or unless a large amount of heat is conveyed to it from a hot interior.

A consequence of the rapid rate of rotation and low density of Saturn is that it is very oblate. The difference between its equatorial and polar diameters is nearly 6700 miles, or about 10 per cent of its whole diameter. Its oblateness is so great that it is conspicuous even through a telescope of 6 inches' aperture.

V. URANUS AND NEPTUNE

187. The Satellite Systems of Uranus and Neptune. — Uranus has four known satellites, two of which were discovered by William Herschel, in 1787, and the other two

by Lassell, in 1851. Their distances are respectively 120,000, 167,000, 273,000 and 365,000 miles, and their periods of revolution are respectively 2.5, 4.1, 8.7, and 13.5 days. Their diameters probably range between 500 and 1000 miles. They all move sensibly in the same plane, but this plane is inclined about 98° to the plane of the planet's orbit; that is, if the plane of the orbits of the satellites is thought of as having been turned up from that of the planet's orbit, the rotation has been continued 8° beyond perpendicularity, and the satellites revolve in the retrograde direction.

Neptune has one known satellite which was discovered by Lassell, in 1846. It revolves at a distance of 221,500 miles in a period of 5 days 21 hours. Its diameter is probably about 2000 miles. The plane of its orbit is inclined about 145° to that of the planet's orbit; that is, the inclination between the two planes is about 35° and the satellite revolves in the retrograde direction.

188. Atmospheres and Albedoes of Uranus and Neptune. — Very little is known directly respecting the atmospheres of Uranus and Neptune. Their low mean densities imply that their exterior parts are largely in the gaseous state. As confirmatory of this conclusion, the spectroscope shows that the light which we receive from them must have passed through an extensive absorbing medium in addition to the sun's atmosphere and that of the earth, through which the light from all planets passes. The absorbing effects of the element hydrogen and water vapor are shown in the spectra of both planets, but, according to the recent results of Slipher, more strongly in the case of Neptune than in that of Uranus. A number of the other absorption bands are due to unknown substances.

The albedo of Uranus is 0.63, and that of Neptune, 0.73.

189. The Periods of Rotation of Uranus and Neptune. — Surface markings have been seen on Uranus by Buffham, Young, the Andre brothers, Perrotin, Holden, Keeler, and other observers, but they have been so indefinite and fleeting

for observation. They are probably in much the same state as Jupiter and Saturn, though, possibly, somewhat further advanced in their evolution because of their smaller dimensions. One thing to be noticed is that they receive relatively little light and heat from the sun. The amounts per unit area are about $\frac{1}{368}$ and $\frac{1}{904}$ that received by the earth. If their capacity for absorbing and radiating heat were the same as that of the earth, their temperatures (Art. 172) would be respectively about $-340°$ and $-364°$ Fahrenheit. Nevertheless, it must not be imagined that even Neptune would receive only feeble illumination from the sun. Although the sun, as seen from that vast distance, would subtend a smaller angle than Venus does to us when nearest the earth, the noonday illumination would be equal to 700 times our brightest moonlight.

XIII. QUESTIONS

1. Find by the method of Art. 172 what the mean temperatures of the earth would be at the distances of Mercury and Venus.

2. If the earth always presented the same face toward the sun, and if there were no distribution of heat by the atmosphere, what would be the mean temperature of its illuminated side? What would be the result if the earth were at the distance of Venus from the sun?

3. If the mean temperature of the equatorial zone of the earth is 85°, and if it receives, per unit area, 2.5 times as much heat as the polar regions, what is the mean temperature of the polar regions, neglecting the transfer of heat by the atmosphere?

4. What would be the mean temperature of the equatorial zone of the earth at the mean distance of Mars?

5. Suppose the mean temperature of the Thibetan plateau at a height of 15,000 feet above sea level is 40°; what would it be if the earth were at the distance of Mars from the sun?

6. Suppose the atmosphere which a planet can hold is proportional to its surface gravity; how does the atmosphere of Mars compare with that of the earth at an altitude of 15,000 feet above sea level?

7. Waiving the temperature difficulties in the hypothesis regarding the habitability of Mars, what reasonable explanation can



CHAPTER X

COMETS AND METEORS

I. Comets

191. General Appearance of Comets. — The planets are characterized by the invariability of their form, the simplicity of their motions, and their general similarity to one another. In strong contrast to these relatively stable bodies are the comets, whose bizarre appearance, complex motions, and temporary visibility have led astronomers to devote to them a great amount of attention. Until the last two centuries they were objects of superstitious terror which were supposed to portend calamities. At least so far as their motions are concerned, they are now known to be as lawful as the other members of the solar system.

The typical comet is composed of a head, or *coma*, a brighter nucleus within the head which is often starlike in appearance, and a tail streaming out in the direction opposite to the sun. The apparent size of the head may be anywhere from almost starlike smallness to the angular dimensions of the sun. The nucleus is usually very small and bright, but the tail often extends many degrees from the head before it gradually fades out into the darkness of the sky. The head is the most distinctive part of the comet, for it is always present and looks much like a circular nebula. Either the nucleus or tail, or both, may be absent, especially if the comet is a small one. Comets vary in brightness from those which are so faint that they are barely visible through large telescopes to those which are so bright that they may be observed in full daylight, even when almost in the direction of the sun. In spite of their being sometimes very



FIG. 119. — Brooks' Comet, Oct. 19, 1911. *Photographed by Barnard at the Yerkes Observatory.*

bright, they are so nearly transparent that faint stars are visible through them without the slightest appreciable diminution of their light.

There are records of about 400 comets having been seen before the invention of the telescope, in 1609, and more than the same number have been observed since that date. Astronomers now keep a close watch of the sky, and only very faint ones can escape their notice. From 3 to 10 are found yearly. They are lettered for each year *a*, *b*, *c*, . . . in the order of their discovery, and are numbered I, II, III, . . . in the order that they pass their perihelia. Besides this, they are generally named after their discoverers.

192. The Orbits of Comets. — In ancient times it was supposed that comets were malevolent visitors prowling through the earth's atmosphere, bent on mischief. Kepler supposed they moved in straight lines, but Doerfel showed that the comet of 1681 moved in a parabola around the sun as a focus. In 1686 Newton invented a graphical method of computing comets' orbits from three or more observations of their apparent positions. Better methods have been devised by Lambert, Laplace, Gauss, and later astronomers, and now there is usually no difficulty in determining the elements of an orbit from three complete observations which are separated by a few days.

The orbits of about 400 comets have been computed, and as nearly as can be determined from the imperfect observations on which the computations of many of them are based, the orbits of about 300 of them are essentially parabolic. In fact, they are so generally parabolic, or, at least, extremely elongated, that it has been customary in the preliminary computations to assume they are parabolas. Of the remaining cometary orbits, nearly 100 have been shown to be distinctly elliptical in shape.

A conic section is an ellipse if its eccentricity is less than unity, a parabola if its eccentricity equals unity, and an hyperbola if its eccentricity exceeds unity. Since a body

moving subject to gravitation may describe any one of these three classes of orbits, and since the eccentricity of a parabola is the limiting case between that of an ellipse and that of an hyperbola, it is infinitely improbable that the orbit of any comet is exactly parabolic.

It is important to determine whether the eccentricities of the orbits of comets are slightly less than unity or slightly greater than unity. In the former case comets are permanent members of the solar system; in the latter, they are only temporary visitors. The difficulty in answering the question is not theoretical, but practical. In the first place, comets are more or less fuzzy bodies and it is difficult to locate the exact positions of their centers of gravity. In the second place, they are observed during only a very small part of their whole periods while they are in the neighborhood of the earth's orbit. Generally they are not seen much beyond the orbit of Mars and very rarely at the distance of Jupiter. For such a small arc the motion is sensibly the same in a very elongated ellipse, in a parabola, and in an hyperbola whose eccentricity is near unity, as is evident from Fig. 120.

More than 80 comets move in orbits whose major axes are so short that they will certainly return to the sun. The remainder move in exceedingly elongated orbits, and the character of their motion is less certain. But it is significant that the recent computations of Strömgren show that in all cases in which comets have been sufficiently observed to give accurate results respecting their orbits, they were moving in ellipses when they entered the solar system. At the present time there is no known case of a comet which was well observed for a long time whose orbit was hyperbolic, and astronomers are becoming united in the opinion that they are permanent members of the solar system.

The orbits of all the planets are nearly in the same plane; on the other hand, the planes of the orbits of the comets lie in every possible direction and exhibit no tendency to paral-

lelism. The perihelia of the orbits of comets are distributed all around the sun, but show a slight tendency to cluster in the direction in which the sun is moving among the stars, a fact which probably has some connection with the sun's motion.

Some comets have perihelion points only a few hundred thousand miles from the surface of the sun, and when nearest

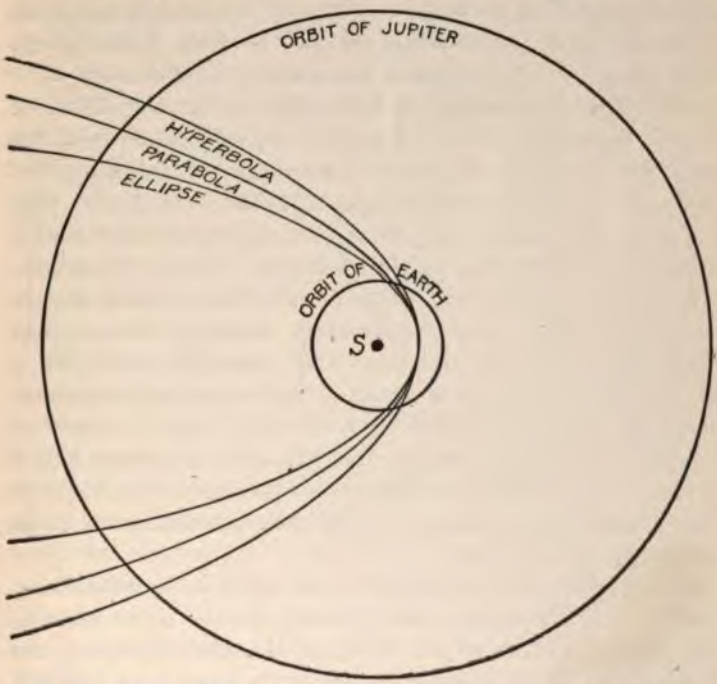


FIG. 120. — Similarity of elongated ellipses, parabolas, and hyperbolas in the vicinity of the orbit of the earth.

the sun they actually pass through its corona (Art. 238). About 25 comets pass within the orbit of Mercury; nearly three fourths of those which have been observed come within the orbit of the earth; very few so far seen are permanently without the orbit of Mars, and all known comets

thousands or hundreds of thousands of miles in their more remote parts. They vary in length from a few million miles, or even less, up to more than a hundred million of miles. In volume, the tails of comets are thousands of times greater than the sun and all the planets together. The strangest thing about them is that they point almost directly away from the sun whichever way the comet may be going. That is, when the comet is approaching the sun, the tails trail behind like the smoke from a locomotive; when the comet is receding, they project ahead like the rays from the head light on a misty night. When a comet is far from the sun, its tail is small, or may be entirely absent; as it approaches the sun, the tail develops in dimensions and splendor, and then diminishes again on its recession from the sun.

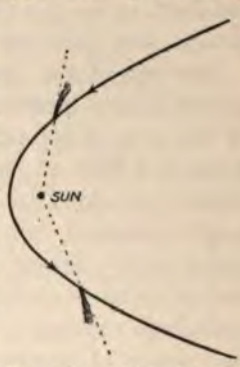


FIG. 121. — The tails of comets are always directed away from the sun.

194. The Masses of Comets. — Comets give visible evidence of remarkable tenuity, but their volumes are so great that, if their densities were one ten-thousandth of that of air at the surface of the earth, their masses in many cases would be comparable to the masses of the planets.

The masses of comets are determined from their attractions for other bodies (Arts. 19, 154). Or, rather, their lack of appreciable mass is shown by the fact that they do not produce observable disturbing effects in the motions of bodies near which they pass. Many comets have had their orbits entirely changed by planets without producing any sensible effects in return. Since, according to the third law of motion, action between two bodies is equal and opposite, it follows that the masses of comets are very small, probably not exceeding one millionth that of the earth.

One of the most striking examples of the feeble gravita-

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remoter planets and is no longer subject to capture by them. The planets beyond the orbit of Jupiter have a few comets each, and the clustering of the aphelia of comets at still more remote distances has suggested the existence of planets as yet undiscovered (Art. 161). The terrestrial planets have no comet families partly because their masses are small compared to that of the sun, and partly because comets cross their orbits at very great speed.

The masses of the planets are not great enough to reduce a parabolic comet to membership in their own families at one disturbance. The matter is illustrated by Brooks' comet, 1889–V, whose period, according to the computations of Chandler, was reduced by Jupiter, in 1886, from 27 years to 7 years. Lexell's comet, of 1770, furnishes an example of a disturbance of the opposite character. In 1770 it was moving in an elliptical orbit with a period of 5.5 years; but in 1779 it approached near to Jupiter, its orbit was enlarged, and it has never been seen again.

When a planet captures a comet, the former reduces the dimensions of the orbit of the latter, but the latter still revolves around the sun. The question arises whether a planet might not capture a comet in a more fundamental sense; that is, reduce its orbit so that it would become a satellite of the planet. It has been repeatedly suggested that the planets may have captured their satellites in this manner. The answer to this suggestion is that a planet cannot capture a comet and make it into a satellite simply by its own gravtation and that of the sun. The only possibility is that the comet should encounter resistance in a very special manner, and even then the problem presents serious difficulties. No small resistance would be sufficient because the motion of a comet around the sun in a parabolic orbit is much greater than it would be in a satellite orbit; and, in order that resistance should reduce the velocity by the required amount, it would be necessary for the comet to encounter so much material that its mass would grow several fold.

computed has moved in a sensibly hyperbolic orbit points strongly to the conclusion that comets have been permanent members of the solar system. They are possibly the remains of the far outlying masses of a nebula from which the solar system may have been developed. With increasing proof that they are actually permanent members of the solar system, their importance in connection with the question of its origin and evolution continually increases.

198. Theories of Comets' Tails. — The fact that the tails of comets usually project almost directly away from the sun indicates that they are in some way acted upon by a repelling force emanating from the sun. The intensity of this repulsion has been computed in a number of cases by Barnard and others from the accelerations which masses have undergone which were receding from the heads of comets along their tails. These accelerations have been determined by comparing photographs of the comets taken at different times separated by short intervals.

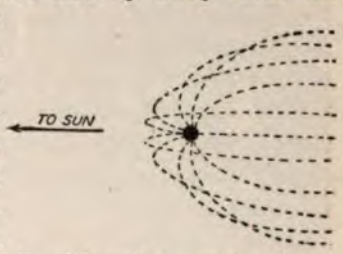


FIG. 123. — The repulsion theory of the origin of comets' tails.

It was suggested by Olbers as early as 1812 that the repulsive force which apparently produces the tails of comets may be electrical in character. This theory has been taken up and systematically developed by Bredichin, of Moscow. According to it, the sun and comet nuclei both repel the material of which the tails of comets are composed. Those particles which leave the nuclei in the direction away from the sun continue on in straight lines; those which leave in other directions are gradually bent back by the force from the sun and form the outer parts of the tails, as shown in Fig. 123. The resulting tails, especially if they are very long, are slightly curved because the motion of the comet is somewhat athwart the line along which the repelled par-

[illegible]

[illegible] repulsion acts on the molecules of particles of particles impinging on their masses. Therefore, while masses are attracted by the sun more than they are [illegible] by the repulsive ray, the true law would [illegible] and the electrical repulsion is relatively stronger the smaller they are. Consequently the tails which are produced of small particles will be more readily straight than [illegible] which are composed of large particles. Besides advancing the theory that the long, straight tails are due to hydrogen gas, the ordinary, slightly curved tails to hydrocarbon gases, and the short, stubby, and much curved tails to vaporized metals, Spectroscopic observations have led to a number of other confirmed [illegible] conclusions. Some comets have tails of more than one type, as for example Donati's comet (Fig. 134).

If the electrical repulsion theory is adopted, the question at once arises why the sun and the materials of which the tails of comets are composed are similarly electrified. A plausible answer to this question can be given. As it is known the hydrogen in the sun's atmosphere seems to be negatively electrified. Suppose a comet approaches the sun from some remote part of space without an electrical charge. Laboratory experiments show that the ultra-violet rays from the sun, striking on the nucleus of the comet, will probably drive off negatively charged particles which will be repelled by the negative charge of the sun, and they will thus form the tail for the comet. The repulsion will depend upon the size of the particles and the electrical potential of the sun. After the negatively electrified particles have been driven off, the nucleus will be positively charged and, consequently, will be electrically attracted by the sun. But since the particles driven off will be only an exceedingly small part of the whole comet, this attraction will not be great enough [illegible] visibly to alter the comet's motion.

the sun, and that sometimes they change their direction by a number of degrees in a very short time. For example, Barnard took photographs of Brooks's comet, 1893-IV, on November 2 and November 3. In this interval the comet moved forward in its orbit about 1°; and, consequently, according to these theories, the direction of its tail should have changed about 1°. But there was an actual change of direction of the tail of 16° which has not been explained. There are also sudden and great changes in the character and luminosity of comets' tails which no theory explains. Sometimes secondary tails are developed with great rapidity, making an angle of as much as 45° with the line joining the comet with the sun. Obviously much remains to be learned in connection with the tails of comets.

199. The Disintegration of Comets. — The particles that leave the head of a comet to form its tail never unite with it again. In this way, at each appearance of a comet, that part of the material which goes to form its tail is dispersed into space; and, as the quantity remaining becomes reduced, the comet becomes less and less conspicuous. Possibly this is one of the reasons why Halley's comet in 1910 was not such a remarkable object as it seems to have been in some of its earlier apparitions.

There is another way in which comets disintegrate. Since their masses are very small, the mutual attractions of their parts are not sufficient to hold them together if they are subject to strong disturbing forces. When they pass near the sun, they are elongated by enormous tides. In fact, they pass within Roche's limit, the tidal forces exceed their self gravitation unless they are as dense as the Comets have such exceedingly small densities that the tidal disintegration for them is very great. Consequently, when a comet passes near the sun, the tides to which it is subject tend to break it apart, the fragments, of course, may be assembled by their mutual attraction after they have receded from the sun.

their way out they may pass near a planet which will exert analogous forces, and may so disorganize them that they will never again be united into a single body.

The theory which has just been outlined is clear. Now what have been the observed facts? Biela's comet was broken into two parts by some unknown forces, and the two components subsequently traveled in independent paths. The great comet of 1882 was seen to have a number of outlying fragments when it was in the vicinity of the sun, and many other comets have exhibited analogous phenomena.

Another source of disturbance to which comets are subject is the scattered meteoric material which may more or less fill the space among the planets. The phenomenon of the zodiacal light gives an almost certain proof of its extensive existence. Such scattered particles would have little effect on a dense body like a planet, but might cause serious disturbances in a tenuous comet. In fact, there are many instances in which comets and comets' tails seem to have been subjected to unknown exterior forces. They are now and then more or less broken up, and occasionally the tails of comets have been apparently cut off and brushed aside.

Many comets which have been observed at two or three perihelion passages have been found to be fainter at each successive return than they were at the preceding, and some have eventually entirely disappeared. It seems to be a safe conclusion that comets are slowly disintegrated under the disturbing forces of the sun and planets and the resisting meteoric material which they may encounter. As confirmatory of this view, it may be noted that the members of Jupiter's family have small tails or none at all; that this comet family does not contain as many members as might be expected; and that a number of comets have totally disappeared, presumably by disintegration.

200. Historical Comets. — In this article some of those comets will be briefly described which have exhibited phenomena of unusual interest. The enumeration of their

peculiarities will illustrate the general statements which have preceded, and will give additional information respecting these remarkable objects.

The Comet of 1680. — The comet of 1680 was the first one whose orbit was computed on the basis of the law of gravitation. Newton made the calculations and found that its period of revolution was about 600 years. It is one of the family of comets mentioned in Art. 195. At its perihelion it passed through the sun's corona at a distance of only 140,000 miles from its surface. It flew along this part of its orbit at the rate of 370 miles per second, and its tail, 100,000,000 miles long, changed its direction to correspond with the motion of the comet in its orbit.



FIG. 125. — Encke's comet (Barnard).

The Great Comet of 1811. — The great comet of 1811 was visible from March 26, 1811, until August 17, 1812, and was carefully observed by William Herschel. He discovered from the changes in its brightness, that it shone partly by its own light; for its brilliance increased as it approached the sun more rapidly than it would have done if it had been shining entirely by reflected light. At one time its tail was 100,000,000 miles long and 15,000,000 miles in diameter. The phenomena connected with it suggested to Olbers the electrical repulsion theory of comets' tails.

Encke's Comet (1819). — Encke's comet was the first member of Jupiter's family to be discovered, and it has a shorter period (3.3 years) than any other known comet. At its brightest it was an inconspicuous telescopic object (Fig. 125), but it is noted for the fact that its period was shortened, presumably by encountering some resistance,

the 30th of September, in the early part of the night, the comet presented an almost normal appearance. Before the night was over, the tail had become cyclonic in form and was attached to the head, which then was small and star-like, by a very slender, curved, tapering neck. On the succeeding night the material that then constituted the tail was entirely detached from the head. On October 15, there was another large outbreak of material which was shown by successive photographs to be swiftly receding from the comet (Fig. 126).

Not only was Morehouse's comet noteworthy for the extraordinary activities exhibited by its tail, but it changed in brightness in a very remarkable manner. It was generally considerably below the limits of visibility with the unaided eye, but now and then it would flash up, without apparent reason, for a day or so until it could be seen very faintly without a telescope. While a number of larger comets have been observed in recent years, no other has given evidence of such remarkable changes in the forces that produce comets' tails, and no other has exhibited such mysterious variations in brightness.

201. Halley's Comet. — Halley's comet is the most celebrated one in all the history of these objects. It is named after Halley, not because he discovered it, but because he computed its orbit from observations made in 1682 by the methods which had been developed by his friend Newton. Halley found that the orbit of this comet was almost identical with the orbits of the comets of 1607 and 1531. He came to the conclusion that these various comets were only different appearances of the same one which was revolving around the sun in a period of about 75 years. The records of comets in 1456, 1301, 1145, and 1066 confirmed this view because these dates differ from 1682 by nearly integral multiples of 75 or 76 years. From his computations Halley predicted that the comet would appear again and pass its perihelion point on March 13, 1759.

time it was so accurately observed that its subsequent orbit could be computed with a high degree of precision. If it had made its next revolution in the same period as the one



FIG. 128. — Halley's comet, May 29, 1910. *Photographed by Barnard at the Yerkes Observatory.*

ending in 1835, it would have passed its perihelion in July, 1912. Instead of this, it passed its perihelion on April 19, 1910. The perturbations of the remote planets reduced its

rival the sun in brightness. One of the reasons for the disappointment was that the earth was not very near the comet when it was at its perihelion where it was brightest and had the longest tail. The relations of the earth, comet, and sun in this part of its orbit are shown in Fig. 129, drawn by Barnard. On May 5, the length of the comet's tail was 37,000,000 miles. On May 18 the comet passed between the earth and the sun and was entirely invisible when projected on the sun's disk. This shows that even its nucleus was extremely tenuous and transparent. At this time the earth passed through at least the outlying part of its tail. Neither at this time nor at any other did the comet have any sensible influence upon the earth. On the whole, it was altogether devoid of interesting features.

II. METEORS

202. Meteors, or Shooting Stars. — An attentive watch of the sky on almost any clear, moonless night will show one or more so-called "shooting stars." They are little flashes of light which have the appearance of a star darting across the sky and disappearing. Instead of being actual stars, which are great bodies like our sun, they are, as a matter of fact, tiny masses so small that a person could hold one in his hand. Under certain circumstances of motion and position, they dash into the earth's atmosphere at a speed of from 10 to 40 miles per second, and the heat generated by the friction with the upper air vaporizes or burns them. The products of the combustion and pulverization slowly fall to the earth if they are solid, or are added to the atmosphere if they are gaseous. Since it is misleading to call them "shooting stars," they will always be called "meteors" hereafter.

The distances of meteors were first determined in 1798 by Brandes and Benzenberg, at Göttingen. They made simultaneous observations of them from positions separated by a few miles, and from the differences in their apparent

directions they computed their altitudes above the surface of the earth (Art. 29). Their observations and those of many succeeding astronomers, among whom may be mentioned Denning, of England, and Olivier, of Virginia, have shown that meteors rarely, if ever, become visible at altitudes as great as 100 miles, and nearly all of them disappear before they have descended to within 30 miles of the earth's surface.

The velocity with which a meteor enters the atmosphere can be found by determining the point at which it becomes visible, the point at which it disappears, and the interval of time during which it is visible. The total amount of light energy given out by a meteor can be determined from its apparent brightness, its distance from the observer, and the time during which it is radiant. The energy radiated by a meteor has its source in the heat generated by the friction of the meteor with the earth's atmosphere, and it cannot exceed the kinetic energy of the meteor when it entered the atmosphere. Suppose all the kinetic energy of a meteor is transformed into light. This assumption is not strictly true, but it will be approximately true for matter moving with the high speed of a meteor. Then, since the energy of motion of a body is one half its mass multiplied by the square of its velocity, the mass of the meteor can be computed because its light energy and velocity can be determined directly from observations by the methods which have just been described. By such means it has been found that ordinarily the masses of meteors do not exceed a few tenths of an ounce. However, the observational data are difficult to determine and the subject has received relatively less attention than it deserves. Consequently, no great reliance should be placed on the precise numerical results.

The Number of Meteors. — If a person scans the sky an hour or so and finds that he can see only a few meteors, he is tempted to draw the conclusion that the number of [illegible] which strike the earth's atmosphere daily is not very

large. He bases his conclusion mostly on the fact that half of the celestial sphere is within his range of vision, but a diagram representing the earth and its atmosphere to scale will show him that he can see by no means half the meteors which strike the earth's atmosphere. As a matter of fact, he can see the atmosphere over only a few square miles of the earth's surface.

From very many counts of the number of meteors which can be seen from a single place during a given time, it has been computed that between 10 and 20 millions of them strike into the earth's atmosphere daily. There are probably several times this number which are so small that they escape observation. Often when astronomers are working with telescopes they see faint meteors dart across the field of vision which would be quite invisible with the unaided eye.

Meteors enter the earth's atmosphere from every direction. The places where they strike the earth and the velocities of their encounter depend both upon their own velocities and also upon that of the earth around the sun. The side of the earth which is ahead in its motion encounters more meteors than the opposite, for it receives not only those which it meets, but also those which it overtakes, while the part of the earth which is behind receives only those which overtake it. The meridian is on the forward side of the earth in the morning and on the rearward side in the evening. It is found by observation that more meteors are seen in the morning than in the evening, and that the relative velocities of impact are greater.

204. Meteoric Showers. — Occasionally unusual numbers of meteors are seen, and then it is said that there is a meteoric shower. There have been a few instances in which meteors were so numerous that they could not be counted, but usually not more than one or two appear in a minute.

At the time of a meteoric shower the meteors are not only more numerous than usual, but a majority of them move so that when their apparent paths are projected back-

nearly 3000 other less conspicuous ones have been found. The Perseids appear for a week or more near the middle of August, the Lyrids on or about April 20, the Orionids on or about October 20, etc.

205. Explanation of the Radiant Point. — In 1834 Olmsted showed that the apparent radiation of meteors from a point is due to the fact that they move in parallel lines, and that we see only the projection of their motion on the celestial sphere. Thus, in Fig. 131, the actual paths of the meteors are AB, but their apparent paths as seen by an observer at O are AC. When these lines are all continued

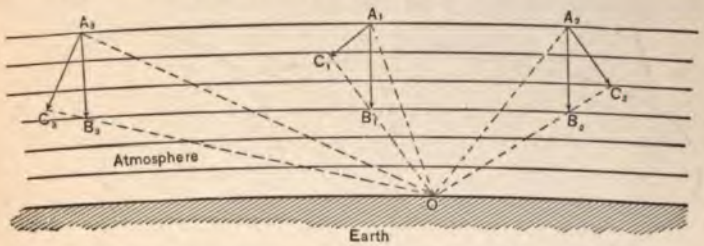


FIG. 131. — Explanation of the radiant point of meteors.

backward, they meet in the point which is in the direction from which the meteors come.

It follows that the meteors which give rise to the meteoric showers are moving in vast swarms along orbits which intersect the orbit of the earth. When the earth passes through the point of intersection, it encounters the meteors and a shower occurs. Thus, the orbit of the Leonids touches the orbit of the earth at the point which the earth occupies on November 14. In this case the earth meets the meteors (Fig. 132), while the Andromids overtake the earth.

206. Connection between Comets and Meteors. — The fact that the volatile material of which comets' tails are composed gradually becomes exhausted, after which the comets themselves become invisible, and the fact that meteoric showers are due to wandering swarms of small

particles which revolve around the sun in elongated elliptical orbits, suggest the hypothesis that comets and meteors are related. The hypothesis is confirmed and virtually proved by the identity of the orbits of certain meteoric swarms and comets.

In 1866 Schiaparelli showed that the August meteors move in the same orbit as Tuttle's comet of 1862. That is, in addition to the comet, which is a member of Saturn's family, there are many other small bodies (meteors) traveling in the same orbit. In 1867 Leverrier found that the Leonids move in the same orbit as Tempel's comet of 1866, while Weiss showed that the meteors of April 20 and the

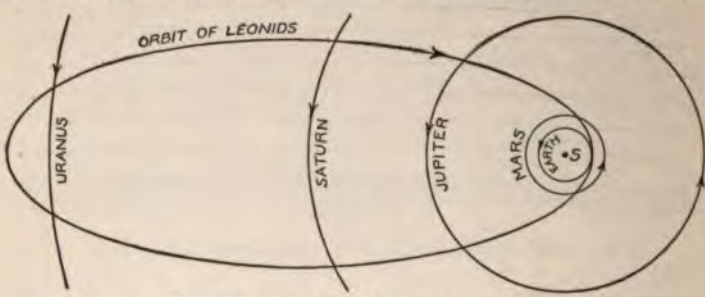


FIG. 132. — Orbit of the Leonid meteors.

comet of 1861 move in the same orbit, and that the paths of the Andromids and Biela's comet were likewise the same. It has recently been claimed that the Aquarid meteors of early May have an orbit almost identical with that of Halley's comet.

While it is not possible to be certain as to the origin of comets, the history of their later evolution and final end is tolerably clear. The elongated orbits in which they may have originally moved are reduced when they are captured by the planets. Their periods of revolution are subsequently shorter, their volatile material wastes away in the form of tails, and the remaining material is scattered along their orbits by the dispersive forces to which they are subject.

If these orbits cross the orbit of a planet, the remains of the comets are gradually swept up by the larger body. If an orbit of a comet does not originally cross the orbit of a planet, the perturbations of the planets will, in general, in the course of time, cause it to do so. The result will be that the planets sweep up more and more of the remains of disintegrated comets and undergo a gradual growth in this manner.

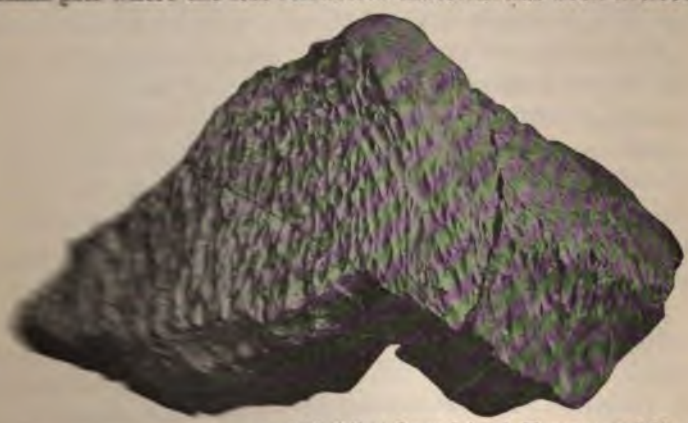
207. Effects of Meteors on the Solar System. — The most obvious effect of the numerous meteors which swarm in the solar system is a resistance both to the rotations and the revolutions of all the bodies. As was stated in Art. 45, the effects of meteors upon the rotation of the earth are at present exceedingly slight, and it is very probable that their influences upon the rotations of the other members of the system are also inappreciable. A retardation in the translatory motion of a body causes its orbit to decrease in size. Hence, so far as the meteors affect the planets in this way, they cause them continually to approach the sun.

Another effect of meteors upon the members of the solar system is to increase their masses by the accretion of matter which may have come originally from far beyond the orbit of Neptune. As the masses of the sun and planets increase, their mutual attractions increase and the orbits of the planets become smaller. Looking backward in time, we are struck by the possibility that the accretion of meteoric matter may have been more rapid in former times, and that it may have been an important factor in the growth of the planets from much smaller bodies.

208. Meteorites. — Sometimes bodies weighing from a few pounds up to several hundred pounds, or even a few tons, dash into the earth's atmosphere, glow brilliantly from the heat generated by the friction, roar like a waterfall, occasionally produce violent detonations, and end by falling on the earth. Such bodies are called *meteorites*, *siderites*, or *aërolites*.

About two or three meteorites are seen to fall yearly; but,

since a large part of the earth is covered with water or is uninhabited for other reasons, it is probable that in all at least 100 strike the earth annually. The outside of a meteorite during its passage through the air is subject to intense and sudden heating, and the rapid expansion of its surface layers often breaks it into many fragments. The surface is fused and on striking cools rapidly. The result is that it has a black, glossy structure, usually with many small pits where the less refractive material has been melted



which fell at Long Island, Kansas; weight, 700 pounds (Farrington).

pass entirely through the atmosphere in their surfaces give evidence of the ex- pressure to which they have been sub- flight.

composed of stone, though it is often iron. Even where pure iron is not compounds are usually found. About hundred are nearly pure iron together about 30 elements which have been found in meteorites, in some respects their structure terrestrial substances. They

have peculiar crystals, they show but little oxidation and no action of water, and they contain in their interstices relatively large quantities of occluded gases, some of which are



FIG. 134. — Iron meteorite from Cañon Diablo, Arizona; weight, 265 pounds (Farrington).

combustible. According to Farrington, some meteors give evidence of fragmentation and recementation, others show faulting (fracture and sliding of one surface on another) with



FIG. 135. — Durango, Mexico. Meteorite showing peculiar crystallization characteristic of certain meteorites (Farrington).

recementation, and others, veins where foreign material has been slowly deposited.

209. Theories respecting the Origin of Meteorites. — If it were known that meteorites are but meteors which are so large that they reach the earth before they are completely

omined and pulverized, we might justly conclude that they are probably the remains of disintegrated comets. This would enable us to learn certain things about comets which cannot be settled yet. But no meteorite is known certainly to have been a member of any meteoric swarm. However, two meteorites have fallen during the time of meteoric showers, one in France, at the time of the Lyrids in 1905, and the other in Mexico, just before the Andromids in 1885.

The structure of some meteorites is more like that of lava from deep volcanoes than anything else found on the earth. An old theory was that they have been ejected by volcanic explosions from the moon, planets, or perhaps the sun. This theory would account for some of their characteristics, and would explain why they contain only familiar elements, as most of the other bodies of the solar system contain only those found on the earth; but it does not at all explain the conglomerations, faulting, and veins, for forces great enough to produce explosions would scarcely be found without heat enough to produce at least fusion.

Chamberlin has maintained that meteorites may be the debris of bodies, perhaps of planetary dimensions, which have been broken up by tidal strains when they have passed near large suns within Roche's limit. When suns pass by one another, it is probable that at rare intervals they pass so near that their planets (if they have any) are broken up. More rarely, the suns themselves may be disrupted. Indeed, this may be the origin of all cometary systems. Whether it is or not, there is here a possibility of disintegration which must be taken into account in any theory of cosmical evolution.

The future promises us more accurate determinations of meteoric orbits to find whether any of them are really hyperbolic, more accurate determinations of the velocities of meteors to find whether they ever come into our system on hyperbolic orbits, and finally the answer to the question whether comets and meteorites are really related.

The suggestion that a meteorite may be a fragment of a world which was disrupted before the origin of the earth makes some demands on the imagination, but it seems no more incredible to us than seemed the suggestion to our predecessors a century ago that great mountains have been utterly destroyed by the rains and snows and winds.

XIV. QUESTIONS

1. What observations would prove that comets are not in the earth's atmosphere, as the ancients supposed they were?

2. Suppose two small masses are moving around the sun in the same elongated orbit, but that one is somewhat ahead of the other. How will their distance apart vary with their position in their orbit (use the law of areas)? Does this suggest an explanation of the variations in the dimensions of comets' heads?

3. The velocity of a comet moving in a parabolic orbit is inversely as the square root of its distance from the sun. At the distance of the earth a comet has a velocity of about 25 miles per second. What is the distance between the comets of 1843 and 1882 when they are 100,000 astronomical units from the sun?

4. Suppose the particles of which a comet is composed have almost exactly the same perihelion point but somewhat different aphelion points. How would the dimensions of the comet vary with its position in its orbit?

5. By means of Kepler's third law compute the period of a comet whose aphelion point is at a distance of 140,000 astronomical units, which is about half the distance of the nearest known star.

6. What objections are there to the theory that originally all comets had an aphelion distance equal to that of Neptune, and that the orbits of some have been increased and others diminished by the action of the planets?

7. On the repulsion theory should a comet's tail be equally long when it is approaching the sun and when it is receding?

8. Draw the diagram mentioned in the first paragraph of Art. 203.

9. Count the number of meteors you can observe in an hour on some clear, moonless night.

10. If possible, observe the Leonid or Andromid meteors.

11. Make a list of the fairly well-explained cometary phenomena, and of those for which no satisfactory theory exists.

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are probably the remains of disintegrat
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CHAPTER XI

THE SUN

The Sun's Heat

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FIG. 136. — The tower [illegible] Institution [illegible]

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ticularly in the question whether or not its rate of radiation is constant. It has long been supposed that probably the sun is slowly cooling off and that the light and heat received from it are gradually diminishing, but it was a distinct surprise when Langley and Abbott found that its rate of radiation sometimes varies in a few days by as much as 10 per cent. If a change of this amount in the rate of radiation of the sun were to persist indefinitely, the mean temperature of the earth would be changed about 13° Fahrenheit; but a variation of 10 per cent for only a few days has no important effect on the climate. Abbott, Fowle, and Aldrich have continued the investigation of this question, and by making observations simultaneously in Algiers, in Washington, and in California, so as to eliminate the effects of local and transitory atmospheric conditions, they have firmly established the reality of small and rapid variations in the sun's rate of radiation.

The question of variation in the amount of energy received from the sun can also be considered in the light of geological evidence. The fossils preserved in the rocks of all geological ages prove that there has been an unbroken life chain upon the earth for many tens of millions of years. This means that during all this vast period of time the temperature of the earth has been neither so high nor so low as to destroy all life. Moreover, the record is clear that, in spite of glacial epochs and intervening warmer eras, the temperature changes have not been very great, and there is no evidence of a progressive cooling of the sun.

212. Sources of the Energy used by Man. — One of the earliest extensive sources of energy for mechanical work used by man was the wind. It has turned, and still turns, millions of windmills for driving machinery or pumping water. Until the last few decades it moved nearly all of the ocean-borne commerce of the whole world, and it is still an important factor in shipping. But that part of the energy of the wind which is used is an insignificant fraction of all that

the physical question of the sun's heat. C... at the rate of the problem of solar radiation rays of all w... ...ssing an area included, and together they constitute the ... of motion were emitted by the sun.

Physicists have devised various metho... ...ed? The sun the amount of energy received from a ... ...rgions of the In applying them to the problem of determi... ...ples, and the of energy received from the sun the chief ... the wind. Con- in making correct allowance for the absorp... ...blows came orig- heat by the earth's atmosphere. The best ... obtained by making simultaneous measur... ...of great practical sea level, from the summits of lofty mou... ...ergy is also the balloons. Langley measured the intensi... ...water and raises ation at the top of Mount Whitney, 14,8... ...carry part of sea, and at its base. He arrived at the ... ...or snow, and in per cent of the rays striking the atmospher... ...and then plunge when it is free from clouds, are absorbed ... ...utilized by men. the surface of the earth; later investiga... ...great waterfalls as this estimate to 35 per cent. The work in... ...normous work the has been continued most successfully by ..., and the equally Aldrich, and they find that the rate at wh... ...falling back to the of all wave lengths is received by the ea... ...of water may fall. the outer surface of our atmosphere wh... ...over 60,000 tons. mean distance is, in terms of mechanic... ...where the annual power per square yard. ...2,000,000 tons of

The earth intercepts a cylinder of ray... ...of half a mile or cross section is equal to a circle whose ... diameter of the earth. The area of thi... ...mechanical work is πr^2, where r equals 3955 × 1760 = 6,96... ...matter which the rate at which solar energy is inter... ...Consequently, earth is in round numbers 230,000,000,... ...plants out of which

In the evolution of life upon the earth... ...their energy from important a factor as the earth itself. ...'s energy broke gists and biologists have a deep intere... ...he atmos- ...rbon was ..., as much

[1] The mean radius of the earth is 3955 miles a mile.

nd given up again as the sun put into

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ds will certainly continue to blow and
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to the earth. At present we are depending
simal residue of the energy which the earth
rlier geological times and which has been
preserved in petroleum and coal.

Amount of Energy radiated by the Sun. — een from the sun subtends an angle of only is, its apparent area is about $\frac{1}{15}$ the greatest of Venus as seen from the earth. A glance show that this is an exceedingly small part of lestial sphere. Since the little earth at a dis-000,000 of miles receives the enormous quantity n in Art. 211, it follows that the amount which by the sun must be inconceivable. It can be thin the range of our understanding only by con-some of the things it might do.

gy radiated per square yard from the sun's surface nt to 70,000 horse power. This amount of heat uld melt a layer of ice 2200 feet thick every hour he surface of the sun; and it would melt a globe of

exists. For example, if, in a breeze blowing at the 20 miles an hour, all the energy in the air crossing 100 feet square perpendicular to its direction of moti used, it would do about 560 horse power of work.

What is the origin of the energy in the wind? warms the atmosphere over the equatorial region earth more than that over the higher latitudes, resulting convection currents constitute the wind sequently, all the energy in every wind that blows ca inally from the sun.

Another source of energy which has been of great value is water power. The source of this energy i sun, because the sun's heat evaporates the water it into the air a half mile or more, the winds car it out over the land, where it falls as rain or sn descending again to the ocean it may now and t over a precipice, where its energy can be utiliz Amazing as are the figures for such great w Niagara, they give but a faint idea of the enorm sun has done in raising water into the sky, and great amount of work the water does in fallin earth. During a heavy rain an inch of wa An inch of water on a square mile weighs ove In the eastern half of the United States, wh rainfall is about 35 inches, every year over 2,(water fall on each square mile from a height more.

The great modern source of energy for me coal. The coal has formed from vegetab accumulated in peat beds ages and ages ago the immediate source of its energy is the pl it has developed. But the plants obtained the sun. In millions of tiny cells the s up the carbon dioxide which they inhale phere; then the oxygen was exhaled an stored up in their tissues. When a plant

ice as large as the earth in 2 h... ...ciples of sci-
than one two-billionth of the ene... ...al in every
is intercepted by the earth, and ... ...of the con-
amount by all the planets toget... ...ation (kinetic
on through the ether to the regi... ...ower it may
of 186,000 miles per second. ...ential energy).

214. The Temperature of the ... ...ergies of the
172) that a black body radiates ... ...be in a radi-
absolute temperature, gives a ... ...ther, or from
temperature of a body whose ... ...ds only when
While the sun is probably not ... ...ed.
contemplated in the statement ... **'s Heat.** — The
it radiates from layers at vari... ...he sun is com-
with the upper layers absorbing ... ...on of the sun
from the lower, yet an approxi... ...articles toward
of its radiating layers can be ob... ...ance one at a
ation. On using Stefan's law ... ...of heat upon
is found that the temperature ... ...ously, first a
sun is at least 10,000° Fahr... ...the same total
accurate to say that an ideal ... ...ght be supposed
perature would have the same ... ...traction would
and since the sun is not a p... ...heat to change
is probably still higher. Th...
sand degrees higher than t... ...onsidered more
efficient electrical furnaces, ...an expanded con-
to melt or vaporize any kn... ...with respect to
the temperature of the int... ...racted, because
far higher. ...changing it from

Another method of deter... ...kinetic energy,
sun is from the proportion of ... ...contraction. It
which it radiates. A bo... ...it is above the
relatively a large amount of ...tial energy; the
blue light. As the temper... ...it loses and the
of blue light increases. Th...
tained by this method of ... ...contraction of
the sun arise, in the first ...

might not supply it with heat to take the place of which it radiates so lavishly. With the insight of Helmholtz saw the nature of the question and fore- probable answer. In 1854, at a celebration in com- tion of the philosopher Kant, he gave a solution of blem under the assumption that the sun contracts h a way as to remain always homogeneous. With esent data regarding its rate of radiation, its volume, mass, it is found by the methods of Helmholtz that, the assumption that it is homogeneous and remains geneous during its shrinking, a contraction of its radius feet per year would produce as much heat as it radi- annually. This contraction is so small that it could be detected from the distance of the earth with our most rful telescopes in less than 10,000 years.

far in this discussion it has been assumed that the sun racts, and the consequences of the contraction have been duced. It remains to consider the question whether under conditions which prevail it actually does contract. The son it does not at once shrink under the mutual gravita- n of its parts is that its high temperature gives it a great dency to expand. As it radiates energy into space its mperature doubtless falls a little; the decrease in tem- rature permits it to contract a little; the contraction pro- uces heat which momentarily restores the equilibrium; nd so on in an endless cycle. This conclusion is certainly orrect, as Ritter and Lane proved about 1870, provided he sun behaves as a monatomic gaseous body. Moreover, Lane established the fact, known as Lane's paradox, that so long as a purely gaseous body cools and contracts, its temperature rises, because, with decreasing volume and greater concentration of matter, the gravitational forces can withstand stronger expansive tendencies due to high temperature. If, with increasing concentration, the laws of gases fail because the deep interior becomes liquid or solid, the temperature might no longer increase.

The question of the variation in the rate of radiation of a contracting sun with increasing age is an important one. Lane showed that, so long as the sun obeys the law of gases, its temperature is inversely as its radius. By Stefan's law the rate of radiation is proportional to the fourth power of the absolute temperature. Consequently the rate of radiation, per unit area, of a contracting gaseous sphere is inversely as the fourth power of its radius. But the whole radiating surface is proportional to the square of the radius. Therefore the rate of radiation of the entire surface of a contracting gaseous sphere is inversely as the square of its radius. That is, according to this theory, the earth received continually more and more heat until the sun ceased to be entirely gaseous, if, indeed, it has yet reached that stage. When the sun's radius was twice as great as it is at present it gave the earth one fourth as much heat, and the theoretical temperature of the earth (Art. 172) was about 200 degrees lower than at present.

217. **Other Theories of the Sun's Heat.** — A number of other hypotheses as to the source of the sun's energy have been advanced, but they are all inadequate. They will be mentioned here in order that the reader may not suppose that they are important, and that astronomers have failed to consider them.

The most obvious suggestion is that the sun started hot and is simply cooling. If it had the very high specific heat of water, at its present rate of radiation its mean temperature would fall 2.5° degrees annually. On referring to its present temperature, it is seen that its radiation could not continue much more than a few thousand years, and that a few thousand years ago its rate of radiation must have been several times what it is at present. These results are absurd and show the falsity of the suggestion.

It is natural to associate heat with something burning, and one naturally inquires whether the heat of the sun can be accounted for by the combustion of the material

of which it is composed. In considering this hypothesis the first thing to be noted is that the same material will burn only once. It is found from the amount of heat produced by coal that if the sun were entirely made up of the best anthracite coal and oxygen in such proportion that when the combustion was completed there would be no residue of either, the heat generated would supply the present rate of radiation less than 1500 years. If none of the heat produced by the combustion were radiated away, and if the specific heat of the sun were unity, the temperature of the sun would rise to only about one third of its present value. Consequently this theory is even less satisfactory than the preceding.

Shortly after the discovery of the law of the conservation of energy the large amount of heat generated by the impact of meteors was established. The heat generated by a meteor striking into the earth's atmosphere at the average rate of 25 miles per second is about 100 times as great as would be produced by its combustion if it were oxygen and anthracite coal. A meteor would fall into the sun from the distance of the earth with a velocity of about 380 miles per second, and since the energy is proportional to the square of the velocity, the heat generated would be about 23,000 times that produced by the combustion of an equal amount of carbon and oxygen. Lord Kelvin supposed that possibly enough meteors strike into the sun to replenish the energy it loses by radiation.

A complete answer to the meteoric theory of the sun's heat is that it requires an impossibly large total mass for the meteors. They could not possibly exist in sufficient numbers within the earth's orbit; and, if they came from without, they would strike the earth in enormously greater numbers than are observed. In fact, computation shows that if the heat of the sun were due to meteors coming into it from all directions and from beyond the earth's orbit, the earth would receive $\frac{1}{2300}$ as much heat directly from the

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from the sun. This is millions of times
receives from meteors, and, conse-
the sun's heat is maintained by the
mable.

Future of the Sun on the Basis

Theory. — The contraction theory of
one of those considered which
conditions a successful theory must
portant source of the sun's heat,
least roughly, how long the
at its present rate, and how
in the future.
the sun had contracted from
possible dispersion, the total
have been less than 20,000,000
annually. If it had con-
the earth's orbit, the amount
enerated would have been
ss. Therefore, according
rth can have received heat
only about 20,000,000
densed at its center, this
5,000,000 years.
theory, the sun will con-
to be gaseous. Probably
3 its temperature will
density will produce
ate of radiation only
contraction is the only
mperature will begin to
the temperature of
and all life on the earth will
a dead and invisible mass,
through space with its retinue of lifeless planets.

The Age of the Earth. — After the development of
tion theory of the sun's heat, physicists, among

whom Lord Kelvin was especially prominent, informed the geologists and biologists in rather arbitrary terms that the earth was not more than 25,000,000 years of age, and that all the great series of changes with which their sciences had made them familiar must have taken place within this time. But no one science or theory should be placed above all others, and other lines of evidence as to the age of the earth are entitled to a full hearing. If they should unmistakably agree that the earth is much more than 25,000,000 years of age, the inevitable conclusion would be that the contraction theory is not the whole truth. This is a matter of the greatest importance, for not only is it at the foundation of the interpretation of geological and biological evolution, but it bears vitally on the question of the age of the stars and on the past and the future of the sidereal universe.

One of the simplest methods employed by geologists for determining the age of the earth is that of computing the time necessary for the oceans to acquire their salinity. The rivers that flow into the oceans carry to them various kinds of salts in solution; the water that is evaporated from them leaves these minerals behind. Consequently the salinity of the oceans continually increases. It is clear that it is possible to compute the age of the oceans from the present amount of salt in them and the rate at which it is being carried into them. Of course, it is necessary to make some assumptions regarding the rate at which salt was carried to the sea in earlier geological ages. The last factor is somewhat uncertain, but this method has led to the conclusion that the interval which has elapsed since the oceans were formed and salt began to be carried down into them is more than 60,000,000 years, and that it is probably from 90,000,000 to 140,000,000 years.

Nearly all the rocks that are exposed on the surface of the earth are stratified. This means that, on the whole, they have been formed from silt carried by the wind and water and deposited on the bottoms of lakes or oceans.

These sediments amount in many places to enormous thicknesses. When it is remembered that the present rocks are largely the result of the simple disintegration and deposition of the original rock material, but that most of them have been repeatedly broken up and redeposited, it is evident that the time required for the great stratification which we observe is enormous. There is obviously much chance for error in any reasoning regarding the rates at which these processes have gone on, but nearly every calculation on this basis leads to the conclusion that the time since the disintegration and stratification of the earth's rocks began is [illegible] years, and most of them have reached much larger figures. The disintegration and total destruction of mountains and plateaus is a closely related process leading to the same results.

In all of the earliest geological formations contain fossils, and these are of primitive forms of life. In later formations the remains of higher forms of plants and animals, finally the vertebrates and the highest forms of life at the present time are found. Obviously a long interval of time has been required for all this change in life forms to have taken place, but no one has made a numerical estimate. Huxley gave the matter consideration and thought a billion years would be a liberal allowance. The recent discovery of mutations in the process of evolution, at least in plants, is more rapid than he supposed; but, on the whole, his estimate of the contraction theory of the sun's heat gives the shortest limits for the age of the earth.

A new, and possibly the best, method of arriving at the age of the earth has followed the discovery of radioactivity. Uranium degenerates by a slow breaking down into radium, lead, and helium are evolved. By measuring the proportions of these products in certain minerals we can compute the time during which degeneration has been going on in them. This method has led

to a greater age for the earth than any other. Strutt, in England, Boltwood, of Yale, and many others have given this method a large amount of study, and have obtained figures reaching up into several hundreds of millions of years. Boltwood, especially, has found that the geologically older rocks show greater antiquity by this method of determining their age, and he reaches the conclusion that some of them are nearly 2,000,000,000 years old.

It is difficult to reach a positive conclusion regarding the age of the earth from this conflicting evidence. The geological methods point to an age for the earth since erosion began of at least 100,000,000 years. Geologists do not see how the facts in any of their lines of attacking the problem can be brought into harmony with the theory that the sun has been furnishing light and heat to the earth for only 25,000,000 years. This discrepancy between their figures and those given by the contraction theory cannot be ignored, and therefore we are forced to the conclusion that the sun has other important sources of heat energy besides its contraction. Aside from this, the fact that a contracting gaseous mass radiates inversely as the square of its radius gives a distribution of the radiation of solar energy altogether at variance with geological evidence.

A possible source of energy for the sun which has not been considered here as yet is that liberated in the degeneration of radioactive elements. It is not certain that uranium and radium exist in the sun, but helium, which is one of the products of the disintegration of these elements, exists there in abundance; in fact, it is called helium because it was first discovered in the sun (Greek, *helios* = sun), and gives presumptive evidence of uranium and radium being there, too. The disintegration of uranium and radium is accompanied by the evolution of an enormous quantity of heat, the energy liberated by radium being about 260,000 times that produced by the combustion of an equal weight of coal and oxygen. These results are startling, and at first it

of the sun were radium or would be almost indefinitely

were radium, heat would
alone as fast as it is now being
years half of the radium would
of heat would correspondingly
in time, only 2000 years
would have been twice as great
production of heat would have been
conclusion is not in harmony
that the sun's heat is largely
of radium is untenable.

which degenerates 3,000,000
In the case of this element
of degeneration presents a difficulty.
uranium, heat would not be pro-
as fast as it is now being radi-
interior of the sun where the tem-
are inconceivably high, the release of
may possibly be much more rapid
conditions, and the process may not
which are radioactive at the sur-
There is no laboratory experience to sup-
because within the range of experiment
radioactive processes have been found to
of temperature and other physical con-
there is something in the suggestion, and
under the conditions prevailing in the sun the
of all elements are released, the amount
be sufficient for hundreds and even thousands
But at once the question regarding the
subatomic energies arises, and, at present, there
to it.

XV. QUESTIONS

1. How many horse power of energy per inhabitant is received by the earth from the sun?

2. What is the average amount of energy per square yard received by the whole earth from the sun?

3. Does the energy which is manifested in the tides come from the sun? What becomes of the energy in the tides?

4. What becomes of that part of the sun's energy which is absorbed by the earth's atmosphere?

5. If the earth's atmosphere absorbs 35 per cent of the energy which comes to it from the sun, how can the atmosphere cause the temperature of the earth's surface to be higher than it would otherwise be?

6. Show from the rate at which the earth receives energy from the sun, the size of the sun, and the earth's distance from the sun, that the sun radiates 70,000 horse power of energy per square yard.

7. Taking the earth's mean temperature as 60° F. and the rates of radiation of the earth (see question 2) and of the sun, compute the temperature of the sun on the basis of Stefan's law.

8. All scientists agree that the earth is more than 5,000,000 years old. On the hypothesis that the contraction of the sun is its only source of heat, and that during the last 5,000,000 years it has radiated at its present rate, what were its radius and density at the beginning of this period? On the basis of Lane's law, what was its temperature? On the basis of Stefan's law, what was its rate of radiation per unit area and as a whole? On the basis of the method of Art. 172, what was the mean temperature of the earth?

II. SPECTRUM ANALYSIS

220. The Nature of Light. — In order to comprehend the principles of spectrum analysis it is necessary to understand the nature of light. A profound study of the fundamental properties of light was begun by Newton, but, unfortunately, some of his basal conclusions were quite erroneous. Thomas Young (1773–1829) laid the foundation of the modern undulatory theory of light. That is, he established the fact that light consists of waves in an all-pervading medium known as the *ether*, by showing that when

two similar rays of light meet they destroy each other where their phases are different, and add where their phases are the same. These phenomena, which are analogous to those exhibited by waves in water, would not be observed if Newton's idea were correct that light consisted of minute particles shot out from a radiating body.

Physical experiments prove that light waves in the ether are at right angles to the line of their propagation, like the up-and-down waves which travel along a steel beam when it is struck with a hammer, or the torsional waves that are transmitted along a solid elastic body when one of its ends is suddenly twisted. In an ordinary beam of light the vibrations are in every direction perpendicular to the line of propagation. If the vibrations in one direction are destroyed while those at right angles to it remain, the light is said to be *polarized*. Many substances have the property of polarizing light which passes through them.

The distance from one wave to the next for red light is about $\frac{1}{40,000}$ of an inch, and for violet light about $\frac{1}{70,000}$ of an inch. There are vibrations both of smaller and greater wave lengths. The range beyond the violet [1] is not very great, for, even though very short waves are emitted by a body, they are absorbed and scattered by the earth's atmosphere before reaching the observer; but there is no limit in the other direction to the lengths of rays. Langley explored the so-called heat rays of the sun with his bolometer far beyond those which are visible to the human eye. The waves used in wireless telegraphy, which differ from light waves only in their length, are often hundreds of yards long.

221. On the Production of Light. — A definite conception of the way in which matter emits radiant energy is important for an understanding of the principles of spectrum analysis, but, unfortunately, the fundamental properties of matter are involved, and physicists are not yet in agreement on the subject. However, the theory that radiant

[1] Excepting the so-called X-rays, which are much shorter.

gy is due to accelerated electrons is in good standing and a correct representation of the principal facts.

The molecules of which substances are composed are themselves made up of atoms. The atoms were generally supposed to be indivisible until the year 1895, when the cathode and X-rays prepared the way for the recent discoveries in radioactivity and subatomic units. In connection with these discoveries it was found that the atoms are made up of numerous still smaller particles, called *electrons* or *corpuscles*. An atom, according to the hypothesis of Rutherford, is composed of a small central nucleus, carrying a positive charge of electricity, and one or more rings

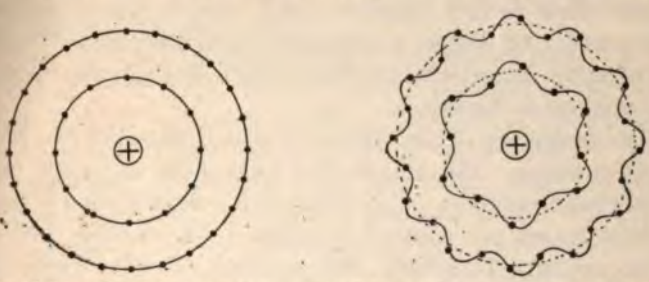


FIG. 137. — Model of atom, non-radiating at left and radiating at right.

of electrons carrying (or perhaps consisting of) negative charges of electricity, which revolve around the positive nucleus at great speed. Under ordinary circumstances the electrons revolve in circular paths with uniform speed, all those of a given ring traveling in the same circle. Under these circumstances, represented in the left of Fig. 137, the atom is not radiating.

When a body is highly heated the molecules and atoms of which it is composed are in very rapid motion and jostle against one another with great frequency. These impacts disturb the motions of the electrons and cause them to describe wavy paths in and out across the circles in which they ordinarily move. This condition is shown at the

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exhibit [illegible] the impacts themselves,
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The d [illegible] of a corpuscle in an atom
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221. O [illegible] seems improbable.
tion of t [illegible] to the corpuscular
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ties of ma [illegible] centrifugal force due to
ment on [illegible] their mutual repulsions

[1] Ex [illegible] electrified. If the
[illegible] all, the atom is stable.

With an increasing number of corpuscles the stability of the atom diminishes. Finally, the atom is stable only if the corpuscles revolve in two or more rings. The regions of instability which separate atoms having a certain number of rings from those having other numbers possibly give a clue to the celebrated periodic law of the chemical elements discovered by Mendeléeff.

222. Spectroscopes and the Spectrum. — The energy which a body radiates is completely characterized by the wave lengths which it includes and their respective intensities. The spectroscope is an instrument which enables us to analyze light into its parts of different wave lengths, and to study each one separately.

There are three principal types of spectroscopes. In the first and oldest type the light passes through one or more prisms; in the second, perfected by Rowland and Michelson, the light is reflected from a surface on which are ruled many parallel equidistant lines; and in the third, invented by Michelson, the light passes through a pile of equally thick plane pieces of glass piled up like a stairway. The first type is most advantageous when the source of light is faint, like a small star, comet, or nebula. Its chief fault is that the scale of the spectrum is not the same in all parts. The second type is advantageous for bright sources of light like the sun or the electric arc in the laboratory. It gives the same scale for all parts of the spectrum, but uses only a small part of the incident light. The third type, known as the *echelon*, gives high dispersion without great loss of light. Only the first type, which is most used in astronomy, will be more fully described here.

The basis of the prism spectroscope is the refraction and the dispersion of light when it passes through a prism. Let L, Fig. 138, represent a beam of white light which passes through the prism P. As it enters at A from a rarer to a denser medium, it is bent *toward* the perpendicular to the surface; and as it emerges at B from a denser to a rarer

medium, it is bent *from* the perpendicular to the surface. This change in the direction of the beam of light is its refraction.

Not only is the beam of light refracted, but it is also spread out into its colors. As it enters the prism the violet light is refracted the most and the red the least, and the same thing is true when it emerges. Consequently, instead of a beam of white light falling on the screen S there is found a band of colors which, in order from the most refracted to the least refracted, are violet, indigo, blue, green, yellow, orange, and red. This separation of light into its colors is called *dispersion*.



FIG. 138.—Refraction and dispersion of light by a prism.

In the diagram only the visible part of the spectrum is indicated. Beyond the red are the infra-red, or heat, rays I-R, and beyond the violet are the ultra-violet rays U-V. The colors are not separated by sharp boundaries, but shade from one to another by insensible gradations. The ultra-violet part of the spectrum is several times as long as the visible part, and the infra-red part is several times as long as the ultra-violet part.

While Fig. 138 shows exactly the way in which a spectrum might be formed, it would be too faint to be of any value in practice. In order to obtain a bright spectrum the apparatus is arranged as sketched in Fig. 139, though in practice several prisms, one after the other, are often employed. The rays which pass through the screen at O are made parallel by the lens L_1. They strike the prism P in parallel lines, and those of a given color continue through P and to the lens L_2 in parallel lines (the dispersion is not indicated in the diagram). The lens L_2 brings the rays to a focus at F, and the eyepiece E sends all those of each color

out in a small bundle of parallel lines (only one color is represented in the diagram). The eye is placed just to the right of E, and all the parallel rays of each bundle are brought to a focus at a point on the retina. In this way many rays of each color are brought to a focus at the same place in the observer's eye.

While strictly white light gives all colors, it is not necessary that a luminous body should emit all kinds of light, or that all colors emitted should be given out in equal intensity. In fact, it is well known that if a body is simply warm but not self-luminous, it gives out in sensible quantities only

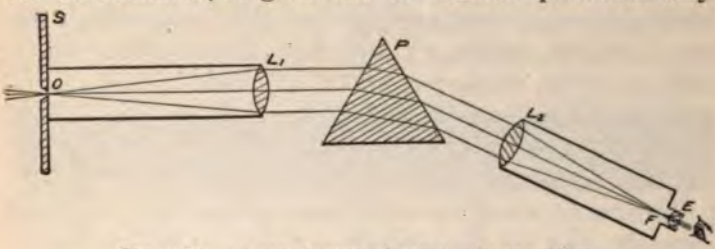


FIG. 139. — A spectroscope having only one prism.

infra-red rays. If it is extremely hot, it may radiate mostly ultra-violet rays.

223. The First Law of Spectrum Analysis. — The first theoretical discussion of the principles of spectrum analysis which reached approximately correct conclusions was made by Ångström in 1853. The work of Bunsen, and especially of Kirchhoff in 1859, put the subject on essentially its present basis. The laws of spectrum analysis as formulated here are consequences of a general law due to Kirchhoff, and of certain experimental facts. After they have been stated, they will be seen to be simple consequences of the mode of production of radiant energy.

The first law of spectrum analysis is: *A radiating solid, liquid, or gas under high pressure gives a continuous spectrum whose position of maximum intensity depends upon the temperature of the source; and conversely, if a spectrum is con-*

[illegible] *[illegible] under high*
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[illegible] radiating solid,
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[illegible]ch.

Spectrum Analysis. — The
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consists of bright lines
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[illegible] not give good results for low
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[illegible]erature, of course, their relations
[illegible] an element are usually identified
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cases to some extent upon its temperature, density, electrical and magnetic condition); and conversely, if a spectrum consists of bright lines, then the source is a radiating gas (or gases) under low pressure, and the composition of the gas (or gases) can be determined from the relations of the lines to one another and from their positions in the spectrum.

When molecules are free from all restraints the oscillations of their electrons take place in fixed periods which depend upon the internal forces involved, just as free bells of given structure vibrate in definite ways and give forth sounds of definite pitch. Consequently, free radiating molecules emit light of one or more definite wave lengths depending on the structure of the molecules, and there are

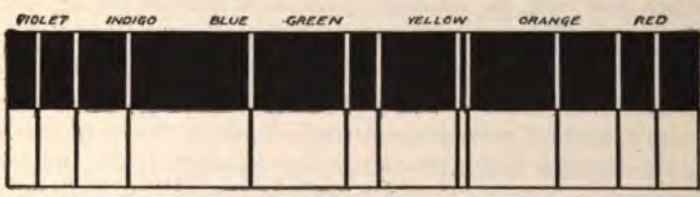


FIG. 140. — A bright-line spectrum above and a reversed spectrum below.

bright lines at corresponding places in the spectrum and no light whatever at other places. A bright-line spectrum is shown in the top part of Fig. 140. Some elements give only a few lines and others a great many. For example, sodium has but two lines, both in the yellow, and iron more than 2000 lines. It is needless to say that all these facts are established by laboratory experiments.

It may be objected that in a gas, even under low pressure, the molecules are not free from outside interference, for they collide with one another many millions of times per second. But the intervals during which they are in collision are very short compared with the intervals between collisions. Consequently, while there will be some light of all wave lengths, it will be inappreciable compared to that which is characteristic of the radiating gas, and the spectrum will seem to con-

list of bright lines of various colors on a perfectly black background.

225. The Third Law of Spectrum Analysis. — The third law of spectrum analysis is: *If light from a solid, liquid, or gas under great pressure passes through a cooler gas (or gases), then the result is a bright spectrum which is continuous except where it is crossed by dark lines, and the dark lines have the positions which would be occupied by bright lines if the intervening cooler gas were the source of light; and conversely, if a bright spectrum is continuous except where it is crossed by dark lines, then the source of light is a solid, liquid, or gas under great pressure, and the light has passed through a cooler intervening gas (or gases) whose constitution can be determined from the relations of the dark lines to one another and from their positions in the spectrum.*

In a word, a cool gas absorbs the same kinds of rays it would give out if it were incandescent, and no others. Similarly, a musical instrument absorbs tones of the same pitch as those which it can produce. For example, if the key for middle *C* on a piano is held down and this tone is produced near by, the piano will respond with the same tone; but if *D* is produced, the piano will give no response. This phenomenon occurs in many branches of physics and is very important. For example, it is at the basis of wireless telegraphy. The receiving instrument and the sending instrument are tuned together, and only in this way do the effects of the feeble waves which reach to great distances become sensible. The fact that the sending and receiving instruments must be tuned the same explains how it is that many different wireless instruments can be working at the same time without sensible interference.

When the intervening cooler gas absorbs certain parts of the energy which passes through it, it becomes heated and its rate of radiation is increased. It might be supposed that this new radiation would make up for the energy which has been absorbed. That which has been absorbed and that

which is radiated are, indeed, exactly equal, but the radiated energy is sent out in every direction and not alone in the direction of the original light passing through the gas. That is, certain parts of the original energy are taken out and scattered in every direction. Therefore, in a spectrum crossed by dark lines the dark lines are not absolutely black, but only black relatively to the remainder of the spectrum. A spectrum of this sort is called an *absorption*, or *dark-line*, or *reversed* spectrum. The reverse of the bright-line spectrum given in the top of Fig. 140 is shown in the bottom part of the figure.

226. The Fourth Law of Spectrum Analysis. — The fourth law of spectrum analysis was first discovered by Doppler and was experimentally established by Fizeau. It is commonly called the Doppler principle, or the Doppler-Fizeau law. It is: *If the source (radiating gas in the case of a spectrum of bright lines, and an intervening cooler gas in case of an absorption spectrum) and receiver are relatively approaching toward, or receding from, each other, then the lines of the spectrum are displaced respectively in the direction of the violet or the red by an amount which is proportional to the relative speed of approach or recession; and conversely, if the lines of a spectrum are displaced toward the violet or the red, the source and receiver are respectively approaching toward, or receding from, each other, and the relative speed of approach or recession can be determined from the amount of the displacement.*

The explanation of the shift of the lines of the spectrum when there is relative motion of the source and the receiver is very simple. If the source is stationary, it sends out wave after wave separated by a given interval; if it is moving toward the receiver, it follows up the waves which it emits and the intervals between them are diminished. That is, the wave lengths have become shorter, which is only another way of stating that the corresponding spectral lines have been shifted toward the violet. Of course, for motion

spectral lines are shifted toward

the source, he receives not
would reach him if he were
which he meets as a conse-
The distances between the waves
spectral lines are shifted toward
opposite direction produces the

in the spectral lines is

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

the shift. λ is the wave length
relative velocity of the source
of light. Suppose v is 18.6
is 186,000 miles per second
the visible spectrum is
the displacement is about
ends of the visible spec-
velocities with which the
of the spectral lines are
must be employed in
The usual method is
the distant object and at
the spectroscope beside it
laboratory source. The lines
their normal positions.
the celestial object with
with the aid of a micro-

object are well defined, dis-
precision can be obtained.
the relative velocities
velocities, can be de-
miles per second.

XVI. QUESTIONS.

1. What problems can be solved approximately for the sun and stars by the first principle of spectrum analysis?

2. What would be the character of the spectrum of moonlight?

3. Comets have continuous bright spectra crossed by still brighter lines; what interpretation is to be made of these facts, remembering that comets shine partly by reflected light?

4. The spectra of Uranus and Neptune contain dark lines and bands of great intensity at the positions of the less intense hydrogen lines of the solar spectrum; what interpretation is to be placed on these phenomena?

5. Can the motion of the earth with respect to the sun and moon be determined by spectroscopic means? The motion of the earth with respect to the planets?

6. If an observer were approaching a deep red star with the velocity of light, what color would the star appear to have? If he were receding with the velocity of light?

7. What effect would the rapid rotation of a star have on its spectral lines?

8. Suppose an observer examines the spectra of the eastern and western limbs of the sun; how would the spectral lines be related? Could they be distinguished from lines due to absorption by the earth's atmosphere?

III. The Constitution of the Sun

227. Outline of the Sun's Constitution. — The apparent surface of the sun is called the *photosphere* (light sphere). It has the appearance of being rather sharply defined, Fig. 141, and it is the boundary used to define the size of the sun, but the sun is disturbed by such violent vertical motions that it is probably very broken in outline. At the distance of the sun from the earth an object 500 miles across subtends an angle of only one second of arc, and, therefore, irregularities in the photosphere would not be visible unless they amounted to several hundred miles. The part of the sun interior to the photosphere is always invisible.

Above the photosphere lies a sheet of gas, probably from 500 to 1000 miles thick, which is called the *reversing layer* because, as will be seen (Art. 233), it produces a reversed,

in the opposite direction the spectral lines a
the red.

If the receiver moves toward the source
only the waves which would reach
stationary, but also those which he m
quence of his motion. The distances be
are diminished and the spectral lines ar
the violet. Motion in the opposite direct
opposite results.

The formula for the shift in the spectral

$$\Delta\lambda = \frac{v}{V}\lambda,$$

where $\Delta\lambda$ is the amount of the shift, λ is
of the line in question, v the relative velo
and receiver, and V the velocity of light.
miles per second; then, since V is 186,000
and the greatest wave length in the vi
nearly twice that of the shortest, the displ
$\frac{1}{10,000}$ of the distance between the ends of
trum. It follows that for the velocities
planets move the displacements of the
very small, and that refined means must
order to determine them accurately. The
to photograph the spectrum of the dista
the same time to send through the spect
the light from some suitable laboratory s
of the latter will of course have their
The displacements of the lines of the cel
respect to them are measured with the
scope.

When the spectral lines of an object are
placement results of astonishing precision
In the case of stars of certain types the
toward or from the earth, called *radial vel*
termined to within one tenth of a mile pe

below that of the remainder of the photosphere. There are other astronomers, however, who believe that the bright nodules are the summits of ascending convection currents, which, by expansion and cooling, are reduced to the state where the most refractory substances partially condense and radiate most brilliantly, while the darker spaces between are where the cooler currents descend.

The photosphere is the region from which the sun loses energy by radiation. This energy must be supplied from the interior. There are three processes by which heat may be transferred from one position to another, viz., by conduction, by convection, and by radiation. Conduction is entirely too slow to be quantitatively adequate for bringing heat to the surface of the sun. Convection currents might be violent enough and might reach deep enough to bring to the surface the requisite amount of heat. In order to get a quantitative idea of the requirements suppose that essentially all of the sun's radiation is from a layer of the photosphere, of average density one tenth, 500 miles thick. Suppose its specific heat is unity. At the rate at which the sun radiates, the temperature of this layer would decrease one degree Fahrenheit in 1.6 hours if fresh energy were not supplied from below. Hence the requirements do not seem to be unreasonably severe.

In a body as nearly opaque as the sun seems to be, radiation probably is of no importance in the escape of heat from the deep interior to the surface layers.

229. Sun Spots. — The most conspicuous markings ever seen on the sun are relatively dark spots which occasionally appear in the photosphere and last from a few days up to several months, with an average duration of a month or two. The typical spot consists of a round, relatively black nucleus, called the *umbra*, and a surrounding less dark belt called the *penumbra*, Fig. 144. The penumbra is made up of converging filaments, or " willow leaves," of brighter material, which look as though the intensely luminous photospheric

to Langley's estimates, they radiate about th
the light. A small portion of the sun's s
magnified is shown in Fig. 143.

The photosphere of the sun gives a continu
Therefore, according to the first law of spect
it is a solid, liquid, or gas under great pressu
photosphere is not transparent there is a stro
to infer that it is liquid, or at least consists
liquid particles (carbon, iron, calcium, etc.)
vapor of simil
But the temp
sun is so hi
conclusion is



FIG. 143. — Small portion of the sun's surface, highly magnified.

In consideri
must be reme
its surface gra
28 times that
and that the p
equal masses
is correspondi
Hence, it is n
ble to supp
pressure dow
corona, chron
reversing layer is great enough to produce
spectrum. The conclusion that the photosph
entirely, if not altogether, gaseous is supporte
that the cooler, overlying reversing layer is
contains some of the most refractory know
The " rice-grain " structure of the photospher
by Abbott as being due to relative motions
different levels analogous to those which produ
sky in the earth's atmosphere. He supposes
places between the " rice-grains " correspond t
where clouds form in our own atmosphere, a
are regions where the temperature has fall

columns were tipped over so as to make their sides vi
The umbra and penumbra do not gradually merge into
other, and likewise the penumbra and surrounding
sphere have a fairly definite line of separation.

The umbra of a sun spot may be anywhere from
50,000 miles across; the diameter of the penumbra
as great as 200,000 miles. When the spots are
dimensions they can be seen simply with the aid of
glass to reduce the glare of the sun. The Chine



FIG. 144. — Great sun spot of July 17, 1905. *Photo*
40-inch telescope of the Yerkes Obs

have records of observations of sun s
before their discovery by Galileo in 16

The umbra of a sun spot is dark only
the glowing photosphere which surrou
light projected on it appears black.
shows many details of darker spots and
most often appear shortly before
neighborhood of spots the brightne
usually above the average, and th
their vicinity very bright elevated
constitute the *faculæ*. These fac

spot divides into two
om each other, some-
ur.
al motions, but until
ught to be hardly char-
n only a small percentage
spectroheliograph (Art.
l means of studying solar
cent years to a discovery
n this connection.
stence of magnetic fields in
ne may well wonder how such
ince we receive only light and
ly it must be done from the
energy which the sun sends to
eman found that most spectral
st widened, when observed along
gnet, and that the two components
d in opposite directions. Hale ex-
spectral lines belonging to sun spots
have the properties of spectral lines in
Then he took up the question of the
tic fields. It was shown by Rowland in
ectric charges in revolution produce elec-
s like those produced by electric currents.
le concluded that the magnetic fields in
ue to vortical motions of particles carrying
charges, and the explanation is almost cer-

tly the whole sun has been found to be involved
ic field whose poles agree approximately with
rotation; it may be analogous to that which
the earth. Schuster has suggested that the mag-
s of the earth and sun may be a consequence of
ions, and that all rotating bodies must be magnets.
discovery is a proof of cyclonic motion in the

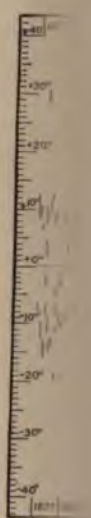
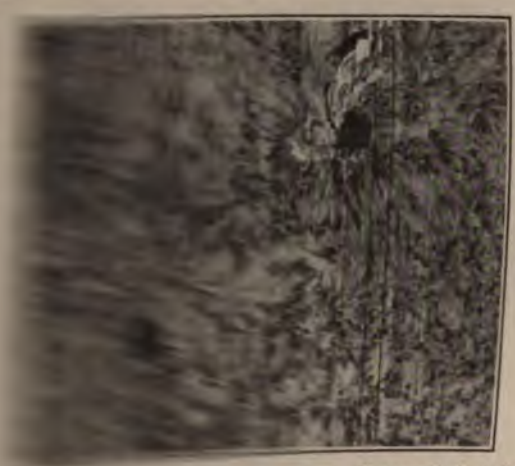


FIG. 14



Photographed at the Mt. ...*graph* (Hale).

231. ... are in the northern hemi- ... ahead has a counter- ... motion in the other is ... are the opposite ... that at the lowest ... outward from spots ... recently St. John, ... (Fig. 147), has made ... spots with the ad-

vantage of most powerful instruments, and he concludes that at the lower levels there is motion radially outward from spot centers, at levels about 2500 miles higher there is no horizontal motion, and in the high levels of the chromosphere (10,000 to 15,000 miles) the motion is inward toward the centers of the spots. This suggests that spots are produced by cooler gases from high levels rushing in toward a center, descending some thousands of miles, and then spreading out at lower levels, but the consideration of the quality and quantity of the materials involved in the two move-



FIG. 147. — The Mt. Wilson Solar Observatory of the Carnegie Institution of Washington. Pasadena, California.

ments, together with their kinetic energies, led St. John to the conclusion that the material flowing inward and downward by no means equals that flowing outward at lower levels from the axes of spots. He believes, rather, that a spot is formed by currents ascending from the sun's interior and spreading out just above the photosphere. The inrushing and descending chromospheric material is a secondary result of the primary currents. The spots are dark because the expanding gases of which they are composed are cooler than those which constitute the photosphere.

Independent evidence of a conclusive character shows that spots are cooler than the ordinary photosphere. There

enhanced spectral lines which
Adams, and Gale: the lines
ed to those in the spectrum
the spectra with low tem-
are related to those with
the spectra of spots con-
believed to be due to ab-
which would be broken up
the higher temperatures of

The Sun. — The rotation of at least
spots occur can be found
across its disk. The first
rotation was made by
idle of the nineteenth
ates from west to east
licular to the plane
to a position whose
ectively 18 h. 44 m.
way between Vega
ation depends upon
complete a revo-
about 26.5 days;
er latitudes spots

FIG.

faculæ, or bright
e neighborhood
are easily de-
n photographs
ion of the sun
s in accord with

fact i
spher
clocky
in the
in the

Ever
visible
parall
at the
extensive

pic methods
heliograph
rotation of
spor, called

flocculi by Hale, and both bright and dark flocculi of hydrogen have been photographed. The rotation of the sun has been determined by Hale and Fox from photographs of flocculi.

Finally, the rotation of the sun has been determined by the Doppler-Fizeau effect. One limb of the sun at the equator approaches the earth at the rate of 1.3 miles per second, while the other recedes at the same velocity. The spectroscopic method is so highly developed that it not only gives the rate of rotation of the sun approximately, but it shows that the period is shorter at the equator than it is in higher latitudes.

The results for the periods of rotation of the sun by the various methods are given in the following table, in which the results are expressed in mean solar days:

TABLE X

LATITUDE	SUN SPOTS	FACULÆ	CALCIUM FLOCCULI	HYDROGEN FLOCCULI	DOPPLER-FIZEAU METHOD
0° to 5°	25.00	24.73	24.76	25.7	24.67
5 to 10	25.09	24.79	24.98	25.0	24.86
10 to 15	25.26	25.12	25.17	24.7	25.12
15 to 20	25.48	25.33	25.48	24.8	25.44
20 to 25	25.75	25.37	25.73	24.5	25.81
25 to 30	26.09	25.64	25.77	24.5	26.20
30 to 35	26.47	26.47	26.18	24.2	26.67

By the Doppler-Fizeau method Adams found the periods of rotation of the sun in latitudes 45°, 60°, and 74°, to be respectively 28.1, 31.3, and 32.2 days.

The reason that the sun rotates in its peculiar manner is not certainly known, though Elliott Smith has attempted to show that the more rapid rotation of the equatorial zone is an inevitable consequence of the contraction of a rotating mass of gas. The question deserves further quantitative examination.

is evidence from the so-called enhanc
has been brought out by Hale, Adam
in the spectrum of spots are related t
of the remainder of the sun just as th
peratures in the electric furnace ar
high temperatures; and finally, th
tain flutings, or bands, which are be
sorption by chemical compounds wh
into their constituent elements in th
the photosphere.

232. The Rotation of the Sun. — T
that part of the sun in which the sp
from their apparent transits acro
systematic investigation of the sun
Carrington and Spoerer about the m
century. They found that the sun
about an axis inclined 7° to the pe
of the ecliptic. The sun's axis pou
right ascension and declination ar
and +46°, which is almost exactly
and Polaris. The period of the sol
the latitude. Spots near the sun's
lution in about 25 days; in latitud
in latitude 45°, in about 27.5 days
are not seen.

Reference has already been mad
clouds, which are especially abun
of sun spots. The positions of
termined on photographs of the s
made at sufficiently short interva
can be found. This method has
those obtained from observations

The remarkable developments
which followed Hale's invention
have furnished a third method of
the sun. By its use bright cloud

esults for about 14,000 spectral lines. A olar spectrum is shown in Fig. 148 with a parison spectrum above.

n of the sun is continuous except for the very lines which cross it. Therefore, in accord- third law of spectrum analysis, there is be- tosphere and the observer cooler gas, and its n be determined from the relations among the d from their positions. The lines prove the odium, iron, and other heavy metals in this as, and since they cannot remain in the gaseous wn atmosphere they must be in that of the sun.



Portion of solar spectrum below with a Titanium comparison spectrum above.

rbing material which overlies the photosphere es the *reversing layer*.

reversing layer could be viewed not projected against liant photosphere, it would give a spectrum of bright ctly at the places occupied by the dark lines under nditions as they normally exist. At the total eclipse sun in 1870, Young placed the slit of his spectroscope t to the limb of the sun. Just as the moon cut off the the photosphere the spectrum suddenly flashed out ght lines where an instant before the dark ones had Since 1895, during nearly every total eclipse of the this " flash spectrum " has been photographed, and is no doubt that the positions of its lines are identical those of the corresponding dark Fraunhofer lines. From duration of their appearance as bright lines and the known at which the moon apparently passes across the disk of

Under the hypothesis that the sun i
in equilibrium, Wilsing, Sampson,
reached the conclusion from hydrodyn
that cylindrical layers of it rotate
According to this view the outermos
cludes only the equatorial zone, rota
cessive cylinders toward the axis rotate
It is supposed that this condition is
primitive state and that friction has
rotation to uniformity. Wilczynski
between the different layers would no
ferences of motion appreciably in ma
But he neglected the convection curr
tainly exist to great depths and which
the supposed different rotations in
Notwithstanding these difficulties, no
is more satisfactory than that the sun
been inherited from more extreme
vailed in the remote past.

233. The Reversing Layer. — New
of light by passing it through a small
1802 Wollaston passed the light from
narrow slit, instead of a pinhole, and
spectrum was crossed by 7 dark lines
subject was taken up by Fraunhofer
the spectrum was crossed by an im
lines. In 1815 he mapped 324 of the
been known as "Fraunhofer lines."
map of these lines was made by Kir
another by Ångström in 1868. In
the solar spectrum with the aid of hi
infra-red region, and in 1886, 1889,
lished extensive and very accurate
of the positions and characteristics
ful grating spectroscope. In 1895
great "Preliminary Table of Solar Sp

layer is 500 or

ing gas is to
red end of
stronomers of
led to the
layer, even at
that of the
ry remarkable
's atmosphere
sun is nearly
earth. Pos-
light pressure
sun.

sing Layer. —
bout one third
sphere, and
versing layer
s of the lines
various ele-
to infer the
produces the
known cer-
of the lines
identified as

re than 2000
m by more
er by 2, and
the elements
ptions being
other hand,
ercury, are
found in the

TABLE XI

ATOMIC WEIGHT	ELEMENT	ATOMIC WEIGHT
1	Copper . . .	64
4	Zinc	65
9	Germanium .	72
12	Strontium . .	88
16	Yttrium . .	89
23	Zirconium . .	91
24	Niobium . .	93
27	Molybdenum .	96
28	Rhodium . .	103
39	Palladium . .	107
40	Silver . . .	108
44	Cadmium . .	112
48	Tin	119
51	Barium . . .	137
52	Lanthanum .	139
55	Cerium . . .	140
56	Neodymium .	144
59	Erbium . . .	168
59	Lead	207

presence of the spectral lines of an element proves , their absence does not show that it is not pres- first place, heavy elements, like gold, mercury, um, would probably sink far below the level of g layer, and consequently would give no lines in pectrum. Then, again, the characteristic spectra the elements, particularly non-metals, are sup- the presence of some other elements, particularly Sometimes the spectrum of an element is entirely by the presence of a small percentage of another This may be the explanation of the fact that the fluorine, chlorine, bromine, iodine, sulphur, sele- llurium, nitrogen, phosphorus, arsenic, antimony, on are not found in the sun, although most of these occur abundantly in the earth. Some elements pectra that change radically with alterations in their

the sun, it has been found that the reversing laye
600 miles deep.

As a rule the effect of pressure on an absorbin
cause the dark lines to shift slightly toward the
the spectrum. Extensive studies by various astr
the displacements of the Fraunhofer lines have
conclusion that the pressure of the reversing lay
its lower levels, does not exceed 5 or 6 times
earth's atmosphere at sea level. This is a very
result in view of the great extent of the sun's
and the fact that gravity at the surface of the s
28 times as great as it is at the surface of the e
sibly electrical repulsion from the sun and lig
partly offset the great surface gravity of the sur

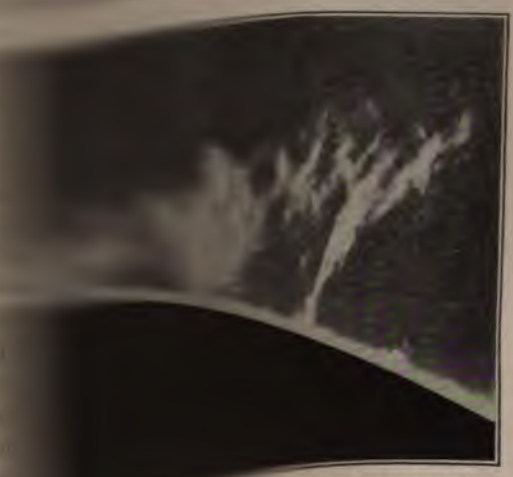
234. Chemical Constitution of the Reversin
Of the 14,000 lines in Rowland's spectrum abo
are due to the absorption by the earth's atmo
the remainder are produced by the sun's rev
and chromosphere. By comparing the position
of the sun's spectrum with those given by the
ments in laboratory experiments, it is possible
chemical constitution of the material which
absorption. In this manner 38 elements are
tainly to exist in the sun, but more than 600
mapped by Rowland have not as yet been
belonging to any element.

The presence of iron is established by mo
line coincidences, carbon by more than 200, cal
than 75, magnesium by 20, sodium by 11, cop
lead by 1. It will be noticed that nearly all
in the table which follows are metals, the exc
hydrogen, helium, carbon, and oxygen. On th
a number of heavy metals, such as gold and
missing. The following table gives the elemen
sun and their atomic weights:

conditions of [illegible] the photosphere with One of these [illegible] per second, and if they in the sun befor[illegible] the reversing layer and of its existence [illegible] entirely from the sun and in abundance [illegible] distances of the stars. yer suggested, [illegible] their great velocities. No reality compou[illegible]ed for explaining how conditions of [illegible] held in restraint and characteristic [illegible]

The reversing [illegible] material from [illegible] conclude that [illegible] from that of the [illegible] that nearly 40 [illegible] strongly to the [illegible] had a common [illegible]

The distributio[illegible] sun's photosphe[illegible] lent photograph[illegible] the eclipse of 1[illegible] the Doppler-Fize[illegible] ments extend to [illegible] are confined to [illegible] that calcium, wh[illegible] dance up into the[illegible] as hydrogen. Iro[illegible] down in the rever[illegible]



[illegible]ching to a height of [illegible] Solar Observatory.

235. The Chrom[illegible] the extreme condi- mosphere is a gas[illegible]g in the interior reversing layer wh[illegible] terrestrial con- gets its scarlet co[illegible] energies. Julius calcium of which [illegible] may be mirage-like

The spectrum of [illegible] and that they are not some of which ar[illegible] seem to be. But their The permanent lin[illegible] their motion perpen- calcium; the interm[illegible] are seen on the sun's [illegible] displacements in accord-

ance with the Doppler-Fizeau principle, and it seems very improbable that they are not real.

The spectra of eruptive prominences show many lines, especially in the lower levels. In them the bright lines of sodium, magnesium, iron, and titanium are conspicuous, while those of calcium, chromium, and manganese are

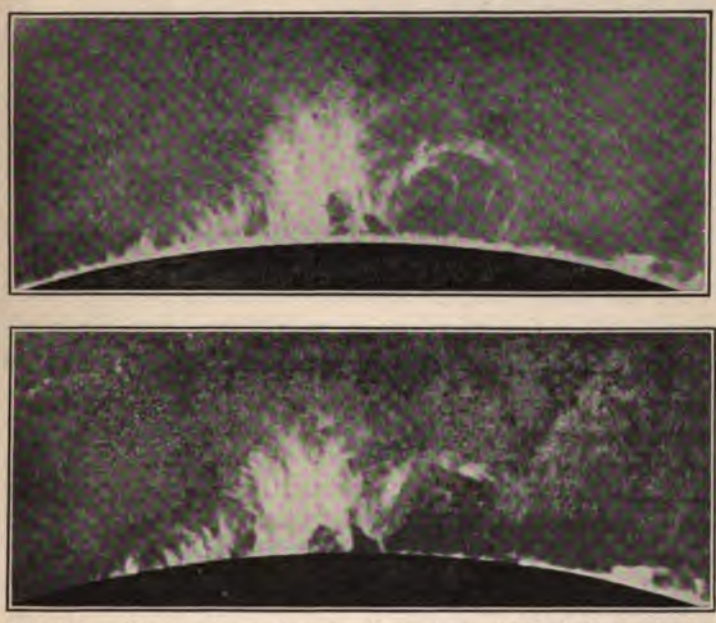


FIG. 150. — Changes in a solar prominence in an interval of ten minutes. *Photographed by Slocum at the Yerkes Observatory.*

generally found. In the higher levels calcium is the predominating element, a remarkable fact in view of its atomic weight of 40.

Prominences were formerly observed only when the sun was totally eclipsed, for at other times the illumination of the sky made them altogether invisible. But since the development of the spectroscope they can be observed at any time. If the light from the limb of the sun is passed through

If eruptive prominences should leave the photosphere a velocity of more than 380 miles per second, and if should suffer no resistance from the reversing layer chromosphere, they would escape entirely from the sun pass out beyond the planets to the distances of the It is very difficult to account for their great velocities satisfactory theory has been developed for explaining such violent explosive forces are long held in restrai

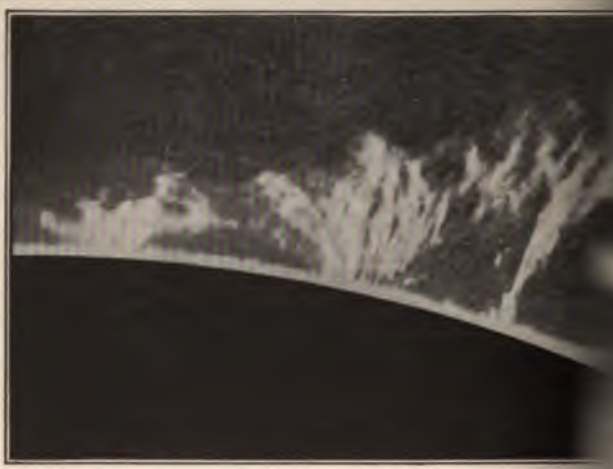


FIG. 149. — Solar prominence, August 21, 1909, reaching to 80,000 miles. *Photographed at the Mt. Wilson Solar Obs*

then suddenly released. Perhaps under the extre tions of temperature and pressure prevailing in t of the sun, all elements, like radium under terre ditions, explode because of their subatomic energi has maintained that the prominences may be appearances due to unusual refraction, and that t actual eruptions from the sun as they seem to be. velocities are determined both from their moti dicular to the line of sight when they are seen o limb, and also from spectral line displacements

the spectroscope, the continuous illumination of the e atmosphere is spread out and correspondingly enfe on the other hand, the light from the prominences co of single colors and is not diminished in intensity by p through the spectroscope. Consequently, if the disp is sufficient, the atmospheric illumination is reduced the prominences become visible.

Not all the prominences are eruptive. Besides which burst out suddenly, rising to great heights and disappearing or subsiding again, there are others, *quiescent* prominences, which spread out, like the t banyan trees, with here and there a stem reaching They often develop far above the surface of the sun, w apparent connections with it, and seem to be due to m which for some mysterious reason suddenly becomes They rest quietly at great altitudes, somewhat like ter clouds, often for many days, notwithstanding th gravity. They are made up of hydrogen, heliu calcium.

237. The Spectroheliograph. — The photospher ates a continuous spectrum, while above it is the re layer which produces the dark absorption lines. Som lines, as the *K*-line due to calcium, are broad becaus great extent of the absorbing layer. Now, calcium i dant in the prominences, and, moreover, it shines intensity greater than that of the reversing layer. sult is that the reversing layer makes a broad, dark li the *K*-line, and above it is more luminous calcium in state which produces a narrow bright line in the m the dark one. The line is said to be "doubly revers

The spectroheliograph is an instrument invented a fected by Hale in 1891 for the purpose of photogr the sun with the light from a single element. The id which it depends were almost simultaneously develop applied by Deslandres. In this instrument, or rathe bination of instruments, the sunlight is passed thro

sun is
led the
e some
So far
vidence
the sun.
tific in-
ing this
of total
in the
is not



versed *H*-line
and 9, 1915.

ere, but is
Fig. 154), in
often simply
ing auroræ.
tailed struc-

erally, have
, but excep-
me way con-
fact that the
eleven years,
n-spot maxima
atitudes nearly

light coming from all depths, particularly from the high layers where absorption is unimportant. On the oth hand, the marginal parts of the line will be due to lig

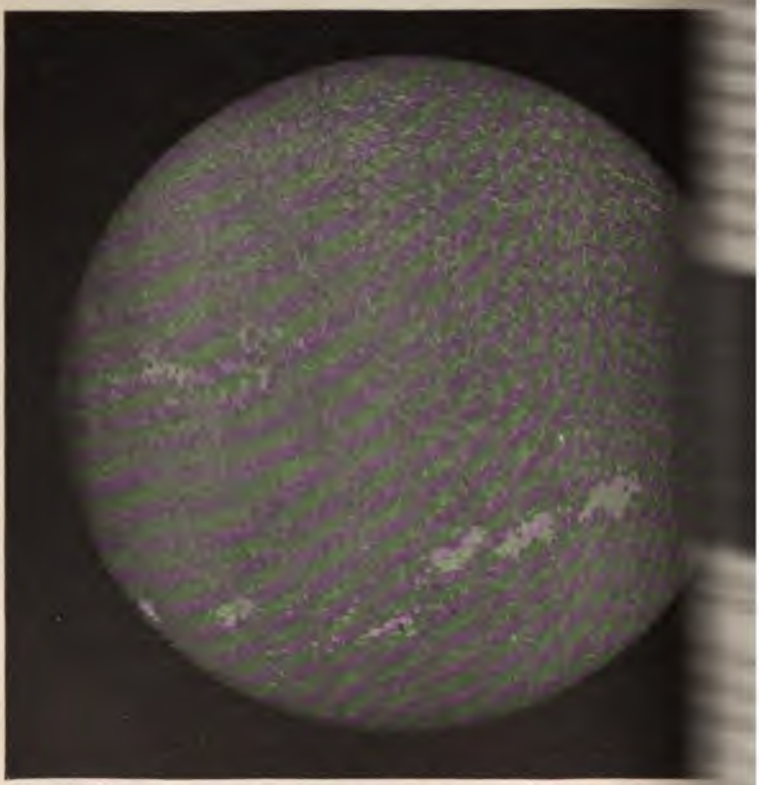
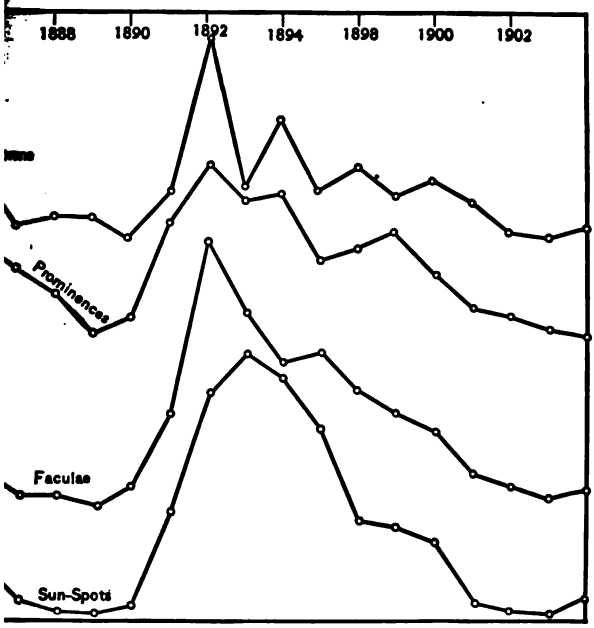


FIG. 152. — Spectroheliogram of the sun taken with the doubly reve calcium line. *Photographed by Hale and Ellerman at Yerkes Observato*

coming from the lower levels where the gas is denser. Fo lowing out these principles, and using a very narrow sli Hale first obtained photographs of different levels of t solar atmosphere.

sted explanation of magnetic storms on the the sun induces changes in the earth's mag- nding out electromagnetic waves. Lord Kel- bjection that if the sun were sending out these direction, it would give out as much energy ordinary electric storm as it radiates in light



ves of magnetic storms, prominences, faculae, and sun spots from 1882 to 1904.

months. A recent exhaustive discussion of the Maunder to the conclusion that the source of nagnetic storms is in the sun, that the magnetic are confined to restricted areas on the sun, and fluences are propagated out from the sun in rotate with the sun; that when these cones of turbances strike the earth, magnetic storms are

239. The Eleven-Year-Cycle.—It has been ... intimate, sun spots vary in frequency and distributio... The most surface in a period averaging a little more ... that there There are a number of other phenomena ... the sun is not changes in the same period.

The faculæ are most numerous in the ... lines of magalthough they occur all over the sun. B... coronal rays, and the positions of the zones where they ... in directions vary periodically with the sun-spot peri... is a little too to be expected, for the sun spots and t... these streams photospheric phenomena. ... forces and

The eruptive prominences are frequ... corpuscles belts, and vary in position with them. ... are phenomena also shows periodic variations in their ... a state not yet cent prominences, on the other hand ... regions.

The coronal types clearly vary ... as was explained in the preceding ... the earth is about total solar radiation varies to some ex... chromosphere, though this has not been verified ... time is now ripe for the investigati... nearer than near

The spectra of sun spots vary w... plained by the abbut the Fraunhofer lines are sing... small solid or liquid

The great vibrations which ... an angle of 1′, sun extend to the earth and pro... be seen simply system. It has long been know... and vertical components of the ... the sun-spot period, and ... ss the sun's disk (''storms'') are most frequent ... aid of the specare most numerous. Likewis... observed? at the epochs of great sun-s... storms and auroræ never occ... activity in the sun in the for... but there are frequent disc... accompanying terrestrial ph... these phenomena is shown ...

CHAPTER XII

...ON OF THE SOLAR SYSTEM

...AL CONSIDERATIONS ON EVOLUTION

...ence of the Doctrine of Evolution. — The ...is on which science rests is the orderliness ... That it is not a chaos has been confirmed ...ous amount of experience, and the principle ...erly is now universally accepted. This princi.le ... in a fundamental respect by the doctrine of

... to the fundamental principle of science the ... was orderly yesterday, is orderly to-day, and will ...ly to-morrow; according to the doctrine of evolu... order of yesterday changed into that of to-day in ...nuous and lawful manner, and the order of to-day ... over into that of to-morrow continuously and sys...tically. That is, the universe is not only systematic ...orderly in space, but also in time. The real essence of ...doctrine of evolution is that it maintains the orderliness ...the universe in time as well as in space.

Evolution may be from the simple and relatively unorgan...ed to the complex and highly organized, or it may be in ...the opposite direction. In fact, evolution generally involves ...the two types of changes. For example, the minerals of the ...soil and the elements of the atmosphere sometimes combine ...and produce a tree having foliage, flowers, and fruit. But ...the tree grows, at least partly, on the disintegrating products ...of other trees or plants, and in its own trunk the processes ...of decay are active. Or, to take a less commonplace example, with the advancement of civilization men have become

induced, and that these magnetic storms have intima
though unknown, relations with sun spots. The m
important contribution of this investigation was that th
is much observational evidence to show that the sun is
to be regarded as surrounded by a polarized magnetic sph
but that there are definite and intense stream lines of m
netic influence, probably connected with the coronal
reaching out principally from the spot zones in direc
which are not necessarily exactly radial. It is a little
early to formulate a precise theory as to whether these str
are electrified particles driven off by magnetic forces
light pressure, or whether they involve the minute corp
of which atoms are composed, or whether they are phen
of matter and energy of a character and in a state n
recognized by science.

XVII. QUESTIONS

1. The apparent diameter of the sun as seen from the earth is 32′; what are the apparent thicknesses of the corona, chromos and reversing layer?

2. The sun's disk is considerably brighter at its center th its margin (Fig. 141); can this phenomenon be explained by sorption of light by the reversing layer? By small solid or particles somewhere above the photosphere?

3. If the smallest spot that can be seen subtends an ang what is the diameter of the smallest sun spot that can be see through a smoked glass?

4. In what direction do sun spots appear to cross the s as a consequence of its rotation?

5. Why cannot the corona be observed with the aid of t troscope at any time, just as the prominences are observed?

more sensitive to discords and more and
appreciating certain types of harmony.
certainly a corresponding improvement in
their nervous system. On the other hand,
ation in the quality of their teeth and ha
in the two directions are both examples

As knowledge increases it is found that
tinually changing. Individuals change, in
languages change, and even the "eternal
up and washed away by the elements in
logical time. Moreover, all these changes
perfectly orderly. The doctrine of evoluti
is so fundamentally sensible and is confi
experience that scientists, the world over
solute confidence. There have been, a
will continue to be, differences of opini
the precise processes of certain particu
have been, but there is no disagreement
the fundamental principles.

241. The Value of a Theory of Evolu
tance of a general principle is proporti
of known facts it correlates. This is a
with special applications in science.
evolution is concerned largely with
the data established by experience, it
attempt at their correlation. Moreov
examined in a critical spirit, so that a
or misconceptions regarding their rel
revealed. Therefore, an attempt to
evolution is of value because it leads t
ing of the material upon which it is b

A theory of evolution invariably
of facts in addition to those upon whi
way it stimulates and directs investig
ity of the investigations which scien
the purpose of proving or disproving

ham, England, pu
of the solar syste
sky. The chief
it gave a straightf
olution. Its chief in
ng philosopher Kan
nce turned his brilli
roblems of cosmogony
lies, and in 1755 he pu
ject. But the world se
of evolution, because
hat of Kant had any in

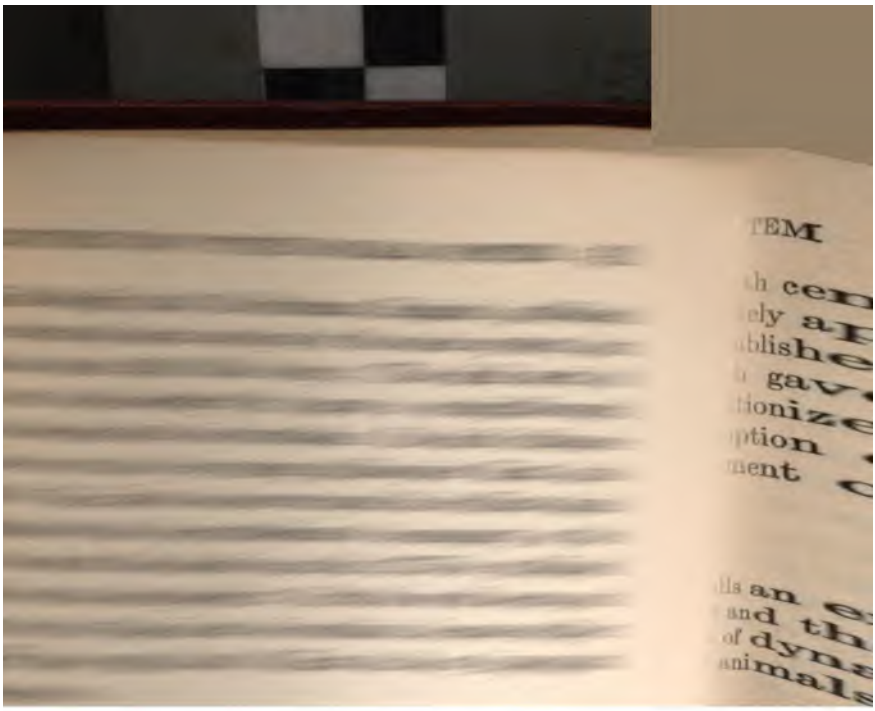
h astronomer and mathe
lebrated "Nebular Hypothe
great name of its author, an
sily understood. Moreover
the world had acquired a
me more receptive of new id
heory of Laplace soon obtai
cientific men. It made a
gists because it furnished them
ly history of the earth. It
urity for an originally hot an
lidified on cooling. It encourag
gical phenomena by geological
ales of the nineteenth century
nd the idea that the earth had
destructive cataclysms, and adopte
ndergone a continuous series of
niform rate.
f the geologists led naturally to th
n of evolution to the biological
e, the belief that the earth was
ome current. In the second plac
le evidences that the surface

"Contemplated as one grand whole, astronomy is the beautiful monument of the human mind, the noblest of its intelligence."

In view of these considerations it is evident that the evolution of the solar system is a subject to which the astronomer naturally gives serious attention. The foremost authorities of the present time have treated the question in lectures, in essays, and in books. When new discoveries are made their bearings on evolutionary theories are at once examined. Astronomers are rapidly approaching the point of view of the biologists, who interpret all of their phenomena in terms of evolutionary doctrines. Yet scarcely a generation ago most astronomers regarded the consideration of the evolution of the solar system as a dangerous speculation.

242. Outline of the Growth of the Doctrine of Evolution. — Every great discovery doubtless has been the culmination of a long period of preliminary work, and before final success has been attained generally many men have approximated to the truth. So it has been with the doctrine of evolution. The ancient Greeks developed theories that everything evolved from fire, or from air and water. These theories contained the germ of the idea of evolution, but their age had not laid securely enough the foundations of science to enable them to treat successfully the development of the universe. After the decline of their intellectual activity the subject of evolution was not considered seriously for many centuries.

In the eighteenth century geologists were groping for a satisfactory theory regarding the succession of the forms whose fossils were found in the rocks. They seem to have concluded on the whole that the earth had been subject to a number of great cataclysms in which all life was destroyed. They supposed that following each destruction of life there had been a new creation in which higher forms were produced. The prevalence of such ideas as these shows what difficulty the doctrine of evolution was developed



...erically, suppose there are
... do not differ from the
...re than 18°, and whose
...s that of the earth. Since
... anything from 0° to 180°,
...en 0° and 18° is $\frac{1}{10}$. The
...rbits of two bodies would
... the probability that the
... is only $(\frac{1}{10})^{800}$, or unity
...hers. This probability is
...nclusion that the arrange-
... system is not accidental.
... this line of reasoning.
... the sun in an orbit of any
... more than 800 planets
... eccentricities less than
... eccentricities less than
... eccentricity greater
...mply that some sys-
... has produced plan-
... both the positions of
... of the orbits of the
... system, in all its
...ortant external dis-

...e Solar System. — Nearly
...ntrated in the sun.
...ss than one seventh
... system. Although
...nes that of all the
... one thousandth that

... masses of the sun
... certainly at pres-
...om one body to
...articles by ejecting

them from its surface in an electrified condition, and a very small percentage of the ejected particles may strike the planets, but it is very improbable that the process has had important effects on the distribution of mass in the solar system, even in the enormous intervals of time required for its evolution.

The mass of the earth is slowly increasing by the meteoric material which it sweeps up in its journey around the sun. It is not unreasonable to suppose that the other planets, and possibly the sun, are growing similarly. This growth, at least in the case of the earth, is too slow at present to have a very important bearing on the evolution of the whole system. But if the meteors are permanent members of the solar system, the more they are swept up by the planets the more infrequent they become and the smaller the number a planet encounters in a day. Consequently, the acquisition of meteoric material by collision may once have been a much more important factor in the evolution of the planets than it is at the present time. In fact, so far as general considerations go, appreciable fractions of the masses of the planets may have been obtained from meteoric material. But it is improbable that the great sun has grown sensibly in this way.

It follows from this discussion that probably the remote antecedent of the solar system consisted of an overwhelming central mass and a very small quantity of matter distributed somewhat irregularly out from it to an enormous distance. At any rate, if this were not the original distribution of matter, the conditions must have been such that the central condensation resulted in harmony with the laws of dynamics. The ever-increasing distances between the planets is shown in Figs. 96 and 97. The relatively small masses of the planets and their enormous distances from one another are among the most remarkable facts that need to be taken into account when considering their origin and evolution.

In or[illegible] be noted is that the ter-
800 bod[illegible] known substances. The
plane of [illegible] (Art. 234), though the
direction [illegible] have not been found.
the incli[illegible] is not so well known,
the chanc[illegible] their low densities and mod-
probabili[illegible] largely only the light
be less [illegible] the origin of the planets,
same wou[illegible] make provision for this
divided [illegible]
so small [illegible]

Momentum. — In at-
ment of [illegible] the solar system it is
Both Kan[illegible] tribution of mass because
A planet[illegible] lar reason, the distribu-
eccentricity [illegible] the system among its
and planeto[illegible] importance. That is,
0.2, the orb[illegible] evolution free from
0.3, and th[illegible] of momentum is
than 0.5. [illegible] beginning and at
tematic cau[illegible]
etary orbits [illegible] inclinations of the
the planes [illegible] centricities of their
planets prov[illegible] has been subject
history, has [illegible] the planets were
turbance, su[illegible] at of the system

244. Distri[illegible] of momentum it
all the matte[illegible] ectly clear, it was
In fact, all th[illegible] dequate consider-
of one per ce[illegible]
the mass of J[illegible] of momentum is
other planets [illegible] ets in such units
of the sun.
It is import[illegible] omentum of the
and planets a[illegible] mputation it
ent no appreci[illegible] ward the in-
another. The [illegible] ly formulated
[illegible] contribute so

little to the final results that it is not important what law of density is used for them.

TABLE XII

BODY	MASS	MOMENT OF MOMENTUM
Sun	0.9986590	0.027423
Mercury	0.0000001	0.000017
Venus	0.0000025	0.000576
Earth	0.0000030	0.000827
Mars	0.0000003	0.000112
Jupiter	0.0009558	0.599273
Saturn	0.0002852	0.241924
Uranus	0.0000430	0.052845
Neptune	0.0000511	0.077003
Total	1.0000000	1.000000

It is seen from this table that although the mass of the sun is 700 times as great as that of all the planets combined, its moment of momentum is only a little over $\frac{1}{10}$ that of the planets. Or, considering the material interior to the orbit of Saturn, it is found that while Jupiter contains only $\frac{1}{10}$ of one per cent, or $\frac{1}{10000}$, of the entire mass, it possesses more than 95 per cent of the moment of momentum.

One at once inquires whether the distribution of moment of momentum is now being changed. The mutual attractions of the planets produce some changes in the distribution of moment of momentum, but they are of no importance whatever in connection with the problem under consideration. The tides which a planet generates in the sun reduce the moment of momentum of the sun and increase that of the planet. But here again the results are inappreciable even for thousands of millions of years. The earth encounters meteoric matter in its revolution around the sun, and it is probable that the other planets are subject to similar disturbances. The result of the resistance by meteors is to reduce the moment of momentum of the planets. At pres-

An additional fact which must be noted is that t
restrial planets contain the heaviest known substances
sun also contains heavy elements (Art. 234), thou
spectral lines of the very heaviest have not been
The constitution of the large planets is not so well
though it may be inferred from their low densities ar
erate temperatures that they contain largely only t
elements. Any hypothesis as to the origin of the
in order to be satisfactory, must make provision
distribution of the elements.

245. Distribution of Moment of Momentum. –
tempting to go back to the origin of the solar sys
natural to consider its mass and distribution of mas
matter is indestructible. For a similar reason, the
tion of the moment of momentum of the system a
various members is of fundamental importance.
if the solar system has undergone its evolution
exterior disturbances, its total moment of mom
now exactly equal to what it was at the beginni
every stage of its development.

As has been stated, the small mutual inclinatio
orbits of the planets and the small eccentricitie
orbits both prove that the solar system has bee
to no important exterior influences since the pla
formed. Hence any hypothetical antecedent of t
must be assigned the quantity of moment of mo
now possesses. Although this fact is perfectly cl
overlooked by Kant and was not given adequat
ation by Laplace and his followers.

In Table XII the mass and moment of mo
given for the sun and each of the eight planets in
that the sums are unity. The moment of momen
sun depends upon its law of density. In the com
was assumed that the mass is concentrated t
terior according to a law of increase of densi
by Laplace. The rotations of the planets

s necessarily
e been about
tion is about
as then quite
not, in some
ial must have
h later became
luce the period
ore specifically,
n contains one
r system within
of the moment
xtreme distribu-
eveloped from an
cially in a mass
able to formulate
ntly, it must be
nt of momentum
ciably since it has

n. — In considering
ission must include
l energy, and sub-

s energy of motion
rnal currents. The
sists of its energy of
ns of its parts. The
the action of exterior
curately known, and
ergy of the system so
countered. Therefore
ion in this connection.
ts change their transla-
the sum of their kinetic
tant.

ent the effects of meteors on the motion of t
inappreciable, but it is not certain that they w
important. However, whether or not they hav
of importance, they cannot relieve the inequa
table, for they are decreasing the moment of m
the planets, which are still relatively very larg
there have been no known influences at work
have sensibly modified the distribution of the
momentum of the system since the sun and
been separate bodies.

It remains to inquire whether the sun and plan
once have been parts of one mass with a dis
moment of momentum quite different from th
present. Since the planets are not receding fr
the only possibility is that the sun and the
formerly so expanded that the material of wh
composed was more or less intermingled.

According to the contraction theory of the hea
the sun's dimensions were formerly greater th
at present. Indeed, the sun has been suppo
once filled all the space now occupied by the pl
lowed backward in time, the sun is found to b
larger, rotating more and more slowly because
of momentum remained constant during cont
more and more nearly spherical because a ro
becomes more oblate with contraction. It follo
table that if the planets which are interior to
added to the sun they would not have an imp
on its moment of momentum.

Now suppose the sun was once expanded out
of Jupiter; its radius was more than 1000 time
radius, its volume was more than $1000^3 = 1$
times its present volume, and its density was
ingly less. Even if it was not condensed towar
the density at its periphery was then less than
of that of the earth's atmosphere at sea level. It

... be done upon it, in virtue of the relati
of its parts, by the forces to which it is subject. I
a body 100 feet above the surface of the earth i
the attraction of the earth. The earth would d
amount of work upon the body in causing it to
altitude of 100 feet to its surface. This work
potential energy of the body in its original p
the case of the translations of the planets, as has
the sum of their kinetic and potential energies
But if the sun or a planet contracts, the potenti
its expanded condition is transformed into heat
which is at least partly lost by radiation. In t
total energy of the system decreases, and the dim
be large in amount.

There is certainly a large amount of subator
uranium, radium, and probably in all other elem
case of the radioactive substances this energy is
formed into heat, which is dissipated by radiat
been suggested (Art. 219), the subatomic ener
liberated in great quantities under the extrem
of pressure and temperature which prevail in
of the sun.

which all revolved in elliptical orbits about the ce
in the same general direction. This organization
satisfies the data of the problem. Moreover,
nebulæ [Art. 302] offer numerous examples of
is apparently in this state.

According to the planetesimal hypothesis,
sun developed from the central parent mass
some outlying parts which fell in upon it becau
small motions of translation. The revolving scat
rial contained nuclei of various dimensions whi
motions about the central sun, swept up the
scattered material and gradually grew into pla
masses depend upon the original masses of the
the amount of matter in the regions through
passed. The angles between the planes of the
gradually reduced by the collisions, and at th
the eccentric orbits became more nearly circu
process of growth the planetary nuclei acquired
rotations.

248. Examples of Planetesimal Organiza
planetoids afford a trace of the former planet
tion of the solar system. The average inclina
average eccentricity of their orbits are consid
than the corresponding quantities for the pla
region which they occupy had been swept by
nucleus, they would have combined with it in a p
ing approximately the mean position of the p
orbits and having a small eccentricity (Art. 25

Another example of planetesimal organiz
nished by the particles of which the rings o
composed. One might at first thought conclu
would have formed one or more satellites if domi
had been revolving around the planet in the
they occupy. But they are very close to Saturn
lite revolving at their distance would be subject
of the tides produced by the planet. As has

center, doubtless [illegible] suns and their distance apart ing at its periphe[illegible] Anapproach within 10,000,000

While a few [illegible] as probable as even a grazing time, their great[illegible] tide-raising force of S' on S began to photog[illegible] gravity of S is more than 2000 Lick Observatory[illegible] times the tide-raising before his death, [illegible] force of the moon on the

"1. Many tho[illegible] earth compared to the sky. A conservat[illegible] surface gravity of the reach of the Cros[illegible] earth. The tide-raising of nebulæ in our [illegible] force varies directly as

"2. These nebu[illegible] the radius of the dis- from the great [illegible] turbed body and in- which is hardly di[illegible] versely as the cube of the

"3. Most of th[illegible] distance of the disturb- While I must le[illegible] ing body (Art. 153). of these conclusio[illegible] Hence, if the nearest direct bearing on [illegible] approach were 5,000,000 cosmogony. If, [illegible] miles, the tide-raising assumed by a co[illegible] force would be more than suggests itself tha[illegible] 8,000 times greater, spiral nebula, wh[illegible] relatively to surface is not, as a rule, o[illegible] gravity, than that of the the contracting m[illegible] moon on the earth. This This is a questio[illegible] force would raise tides Chamberlin and [illegible] approximately 500 miles

While the spira[illegible] high if the sun were a etesimal organizat[illegible] homogeneous fluid, and are enormously l[illegible] restriction of the sun unless, indeed, th[illegible] The tides on a the orbit of Neptu[illegible] probably be much higher. lower limit to the [illegible] forces which now and it is possible [illegible] nces to distances moderate size.

249. Suggested [illegible] validity of the pl[illegible] be mostly toward [illegible] the ejections would

reach to greater distances in these directions. Besides this, after the ejected material had once left the sun, its distance would be increased still further by the attraction of S'. Consequently, if S' were not moving along its orbit, the ejections toward and from it would be to more remote distances than they would be in any other direction. In fact, those toward S' might even strike it. But S' would be moving along in its orbit, and, in a short time, it would have a component of attraction at right angles to the original direction of motion of the ejected matter. Consequently, by the time S' had arrived at S_2', the paths of the ejected masses would be curved somewhat like those shown in Fig. 156. It is easy to see that, for the mass ejected toward S', the curvature is in the right direction; a discussion based on the resolution of the forces involved (Art. 153) proves that, for the mass ejected in the other direction, the indicated curvature is also correct. Eventually S' would move on in its orbit so far that it would no longer have sensible attraction for the ejected masses, and they would be left revolving around S in elliptical orbits. If the initial speed of the ejected material were very great, it might leave S never to return.

The critical question is whether matter would be ejected far enough to produce the large orbits required by the theory. In order to throw light on this question the following table has been computed, giving the surface velocities necessary to cause undisturbed ejected matter to recede various distances from the surface of the sun.

The most remarkable thing shown in the table is that after a velocity is reached sufficient to cause the ejected matter to recede a few millions of miles, a small change in the initial speed produces radically different final results. Since prominences now ascend to a height of half a million of miles without the disturbing influence of a visiting sun, it is seen that the numerical requirements of the hypothesis are not excessive. Moreover, numerous actual computations of

relative masses of [illegible] fast, on the recession of S', compared to the radius [illegible] left revolving around S in miles is more than [illegible] collision. At this dis[illegible] compared to the [illegible]

[illegible] of Ascent	Initial Velocity
[illegible],000 mi.	353 mi. per sec.
[illegible],000 mi.	368 mi. per sec.
[illegible],000 mi.	376 mi. per sec.
[illegible],000 mi.	380 mi. per sec.
[illegible],000 mi.	382 mi. per sec.
[illegible],000 mi.	383 mi. per sec.
[illegible]	384 mi. per sec.

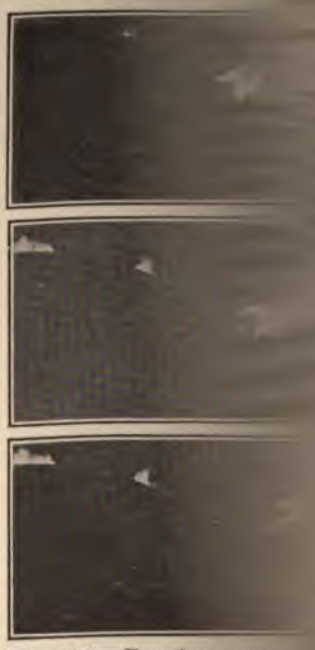


Fig. 157. — Eruptive prominences at different altitudes. *Photographed by the Yerkes Observatory.*

[illegible] of material is more [illegible] star is far away, the [illegible] the matter returns to [illegible] the sun. As the visiting star approaches, the ejected materials recede farther and their paths become more curved. At a certain time the lateral disturbance of S' becomes so great that the ejected material revolves around S instead of falling back upon it. Let the [illegible] t' in Fig. 158, the [illegible] away from it. At a [illegible] distances and the [illegible]. Suppose they [illegible] until S' recedes

there would be a corresp[illegible] in a belt midway betwe[illegible] highly heated gaseous bo[illegible]

The sun is the seat of [illegible] often eject matter in the [illegible] of several hundred thou[illegible] were tidally distorted, th[illegible] and from the disturbing [illegible]

Now consider the location of all of the ejected material at a given time after S' has passed its nearest point to S. If it has been sent out from S continuously, it will lie along two continuous curves, represented by the full lines in Fig.

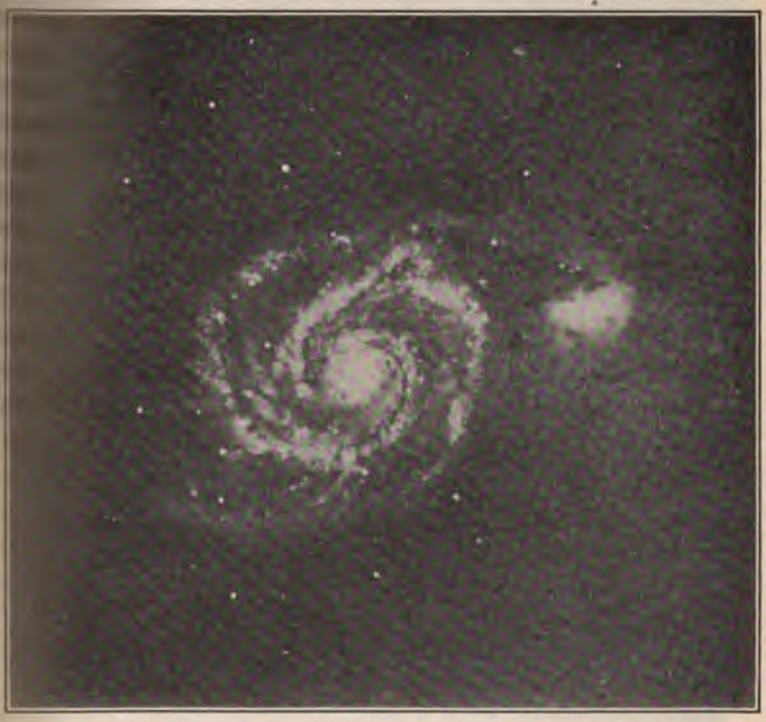


FIG. 159. — The great spiral nebula in Canes Venatici (M. 51), showing the two arms. *Photographed by Ritchey at the Yerkes Observatory.*

158. These are the arms of the spiral nebula whose individual particles move across them in the dotted lines. The diagram shows an ideal simple case, and Fig. 159 an actual photograph. But if the approach of S' were close, or if there were a partial collision, and if the ejected material should go beyond S', a very complicated structure would result. The

... be very irregular (Fig. 160), the ... at a great variety of angles, and ... to recede indefinitely.



FIG. ... (M. 33). *Photographed* ... *Observatory.*

orbits ... the origin of the spiral
former ... great number of stars,
later time ... motions which
materials ... their eruptive activities,
are 2 and 2 ... another passing near it.
from *S*.

All the factors involved are well established — the only question is that of their quantitative efficiency. Here some doubts remain. It follows from the number of stars, the space they occupy, and their motions that, if they were moving at random, an individual sun would pass near some other one, on the average, only once in many thousands of millions of years. Perhaps the mutual gravitation of the stars is important out on the borders of the great clusters of suns of which the Milky Way is composed, where it may reasonably be supposed that their relative velocities are small, and it may be that in these regions close approaches are for this reason much more frequent. But in any case the demands of time are very formidable. Besides this, many of the spiral nebulæ are of such enormous dimensions that it is difficult to suppose they have been produced by the encounter or near approach of ordinary suns. It may be stated, however, that, in the first place, there is no positive knowledge whatever respecting the masses of spiral nebulæ; and that, in the second place, near approaches are not confined to single stars, but may involve multiple stars, clusters, and systems of stars. The observed spirals may be simply the larger examples originating from several or many suns.

It should be remembered that, whatever doubts may remain respecting the validity of this or any other hypothesis, the spiral nebulæ certainly exist in great numbers, and they apparently have, on an enormous scale, an organization similar to that which we have inferred must have been the antecedent of the solar system. And it may be stated again that the planetesimal hypothesis rests primarily upon the evidence now furnished by the solar system, and that it does not stand or fall with any theory respecting spiral nebulæ.

250. The Origin of Planets. — According to the planetesimal hypothesis, the parent of the solar system consisted of a central sun surrounded by a vast swarm of planetesimals which moved approximately in the same plane in essentially independent elliptic orbits. Among these

planetesimals there were nuclei, or local centers of condensation, which, in their revolutions, swept up the smaller planetesimals and grew into planets. It is not to be understood that the original nuclei were solid or even continuous masses. It is much more probable that in their early stages they were swarms of smaller masses having about the same motion with respect to the central sun, and that, under their mutual attractions and collisions, they gradually condensed into continuous bodies. Indeed, the condensation may have been very slow and may have been dependent to an important extent upon the impacts of other planetesimals.

It seems to be impossible to determine the probable masses of the original nuclei. If they were less than that of the earth at present, they could not have retained any atmospheres under their gravitative control. But as the nuclei grew, their surface gravities increased, and a time came when those which have become the larger planets possessed sufficient gravitative power to prevent the escape of atmospheric particles. The acquisition of atmospheres was then inevitable because, in the first place, the materials grinding together and settling under the weight of accumulating planetesimals would squeeze out the lighter elements; in the second place, the pulverizing and heating effects of the impacts of meteors would liberate gases; and, in the third place, the growing planets in their courses around the sun would sweep up directly great numbers of atmospheric molecules. The extent of the atmospheres of the planets depended on the stages of their growth depended primarily on their

The rate at which the nuclei swept up the planetesimals must have been extremely slow. This conclusion follows from the fact that the matter in the largest planet were scattered around the sun in a zone reaching halfway to the adjacent planets, the resulting planetesimals would be very far from each other, as is shown by the fact that the orbits of only a fraction of them would at any one time intersect the orbit of the

nucleus. It must be remembered that the orbits of the planetesimals were continually changed by their mutual attractions and especially by the attractions of the nuclei. Moreover, the orbits of the nuclei were continually altered by collisions with the planetesimals and by their perturbations of one another. Consequently, if the orbits of the nuclei and certain planetesimals did not originally intersect, they might very well have done so later. But it does not follow that they have all been swept up yet, or, indeed, that they all ever will be swept up. Possibly some of the meteors which the earth now encounters are the straggling remains of the original planetesimals.

If the planetesimal theory is correct, the earth is very old and the sun must have important sources of energy besides its contraction. Most of the geological processes did not begin until it became large enough to retain water and an atmosphere. These same conditions were necessary for even the beginnings of the development of life, which may have had a continuous existence from the time the earth was half its present size.

251. The Planes of the Planetary Orbits. — If the planetesimal hypothesis is true, it must explain the important features of the solar system. The most striking thing about the motions of the planets is that they all go around the sun in the same direction, and the mutual inclinations of the planes of their orbits are small. However, some deviations exist, and in general they are greatest in case of the small masses like Mercury and the planetoids.

It is assumed that the planetesimals all revolved around the sun in the same direction. This would certainly have been true if they originated by the close approach of two suns, as explained in Art. 249. But the planes of their orbits would not be exactly coincident. The plane of motion of an ejected particle would depend upon its direction of ejection and the forces to which it was subject. The ejections would be nearly toward or directly away from the visit-

planetesimals there were nuclei, or local centers o
tion, which, in their revolutions, swept up the sm
esimals and grew into planets. It is not to be
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round the sun. Collisions will
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me dimensions; if the orbits of
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ion that if two bodies are moving in
d shape, but differently placed, and
way, the eccentricity of the orbit of
ll be smaller than the common eccen-
the separate parts.[1]

a nucleus M and a planetesimal m are moving in
n-axis and eccentricity are a_0 and e_0. Let their
preceding collision be V_0 and v_0, and their combined
be V. The kinetic energy of the two bodies at the
llision is $\frac{1}{2}(MV_0^2 + mv_0^2)$. Their kinetic energy after
$+ m)V^2$. The latter will be smaller than the former
gy will have been transformed into heat by the impact of
herefore $MV_0^2 + mv_0^2 > (M + m)V^2$.
celestial mechanics in the problem of two bodies that in
$V^2 = \frac{2}{r} - \frac{1}{a}$. Hence, the inequality becomes

$$M\left(\frac{2}{r} - \frac{1}{a_0}\right) + m\left(\frac{2}{r} - \frac{1}{a_0}\right) > (M + m)\left(\frac{2}{r} - \frac{1}{a}\right),$$

the major semi-axis of the combined mass. It follows from this
that $\frac{M + m}{a_0} < \frac{M + m}{a}$, whence $a < a_0$. That is, under the cir-
ces of the problem a collision always reduces the major semi-axis of
it.
ther principle established in celestial mechanics is that the moment

ing sun, but slight devi
the ejecting body might l
direction of ejection would
rotation.

Consider, therefore,
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The system of planetoi
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They gradually sweep up
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252. The Eccent
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cent of the sun's mass.

Another interesting result remains to be mentioned.
planetesimals would strike the equatorial region of the s
in greatest abundance and would give it the most rapi
motion. Unless the inequalities in motion were worn down
by friction the equatorial zone would be rotating fastest, as
is the case with our own sun.

254. The Rotations of the Planets. — The earth, Mars,
Jupiter, and Saturn rotate in the direction in which the
planets revolve; the surfaces of the other planets have not
been observed well enough to enable astronomers to deter-
mine how they rotate. It has been generally supposed that
the equators of Uranus and Neptune coincide with the
planes of the orbits of their satellites, but the evidence in
support of the supposition is as yet inconclusive.

The earlier theories regarding the origin of the planets all
fail to explain their forward rotations.

Chamberlin has shown that if a planet develops from
a planetesimal system it will in general rotate in the direc-
tion of its revolution. Consider a nucleus N, Fig. 161,
which, in its early stages, will probably be simply an immense

Of course, if two orbits were of exactly the s
periods of the bodies would be the same and coll
result either at the first revolution or only after
attractions had modified their motions. But
of nearly the same size, the conditions for collisi
favorable, and in nearly all cases the eccentrici
reduced.

It follows from this discussion that, in gene
between planetesimals cause the eccentricities o
to decrease. Consequently, the more a nucle
sweeping up planetesimals, the more nearly circul
its orbit will be. If a nucleus revolves in a r
planetesimals, the result is likely to be a large p
orbit has small eccentricity. These conclusion
cisely with what is found in the solar system, fo
all the large planets are nearly circular, while
some of the smaller planets and many of the p
considerably eccentric.

253. The Rotation of the Sun. — If the cen
the planetesimal system rotates in the direction o
of the outlying parts, the final result will be a
in the direction of revolution of its planets.
planetesimal organization is the result of the cl
of two suns, the central mass might originally
rotating in any direction. In this case the fi
is not quite so obvious.

The only planetesimals which could sensibly
rotation of the central mass are those which fal
it. If the planetesimals originated by the clos

of momentum is constant whether there are collisions or not
moment of momentum of a mass m is $m\sqrt{a(1-e^2)}$, where
tricity. The condition that the moment of momentum
shall equal that after collision is, therefore,

$$M\sqrt{a_0(1-e_0^2)} + m\sqrt{a_0(1-e_0^2)} = (M+m)\sqrt{a(1-e^2)}, \text{ or}$$
$$\sqrt{a_0(1-e_0^2)} = \sqrt{a(1-e^2)}.$$

Since $a_0 > a$, it follows that $\sqrt{(1-e_0^2)} < \sqrt{1-e^2}$, and therefore

swarm of planetesimals. For simplicity, suppose is a circle C around the sun as a center (if this ass were not made, the discussion would not be essentia fied). The planetesimals which can encounter N ar into three classes: (a) those whose aphelion po inside the circle C; (b) those whose perihelion po inside C and whose aphelion points are outside of (c) those whos lion points are o C. They are de by (a), (b), an spectively in Fi

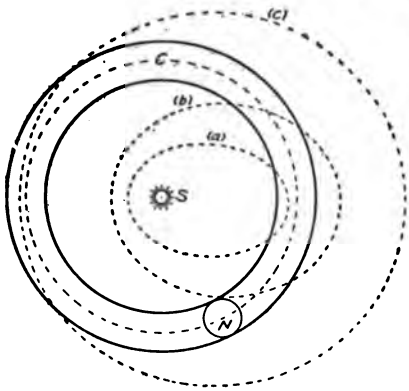


FIG. 161. — Development of the forward rotation of a planet nucleus by the accretion of planetesimals.

Consider coll the planetesi class (a) with cleus N. A can occur only planetesimal is aphelion point. near this po planetesimal is slower than cleus.[1]

Hence the nucleus will overtake the planetesimal collision will be a blow backward on the inner si nucleus. That is, planetesimals of class (a) tend t nucleus a forward rotation.

Planetesimals of class (b) can strike the nucleu tend to give it a rotation in either direction, or so have any effect on its rotation. If they are not d in some special way, the collective result of the c many of them will be very small.

[1] Let V and v represent the velocity of the nucleus and respectively, and A and a the semi-axes of their orbits. It celestial mechanics that $V^2 = \frac{2}{r} - \frac{1}{A}$, and $v^2 = \frac{2}{r} - \frac{1}{a}$. Since a the same in the two equations, it follows that $V^2 > v^2$.

esimal theory, the satellites developed either from secondary nuclei which were associated with the planetary nuclei from the beginning, or from neig secondary nuclei which became entangled at a later the outlying parts of the swarms of planetesimals co ing the nuclei. If the satellites originated in the form their directions of revolution would be the same as t rotation of their respective primaries; if in the latt they might revolve originally in any directions arou primaries.

With the exception of the eighth and ninth satel Jupiter and the ninth satellite of Saturn (and possi satellites of Uranus and Neptune), all the known s revolve in the directions in which their primaries This seems to indicate that at least most of the s originated from secondary nuclei which were associat their respective primary nuclei from the beginning a took of their common motion of rotation. The s nuclei, like the planetary nuclei, swept up the planet and grew in mass. The craters on the moon ma been produced by the impact of planetesimals.

With the growth in mass of a planet its attraction satellites increases and this results in a reduction dimensions of their orbits. Suppose the most remot

factor in the
force of energy
on many tens
clude that the
se the earth

for this reason, and it is not impossible that other
also once had ring systems.

257. The Planetoids. — The planetoids occupy a
which there was no predominating nucleus. They pr
have not grown so much relatively as the planets
accretion of planetesimals. Hence the ranges in the
tricities and inclinations of their orbits give a bette
of the character of the orbits of the original planetesin

Besides the known planetoids, there are probably
sands of others which are so small that they have no
seen. There may be others also between the orb
Jupiter and Saturn and beyond the orbit of Satur
those vast distances none but large bodies would be
both because they would not be strongly illuminat
the sun and also because they would always be very
from the earth. The planetoid Eros has escaped c
with Mars only because of the inclination of its orbi
is not unreasonable to suppose that there are many
planetesimals between the orbits of the earth and
which are too small to be visible.

258. The Zodiacal Light. — It is universally agree
the zodiacal light is due to a great swarm of small
or particles, revolving around the sun near the plane
earth's orbit. These small bodies are in reality pla
mals which have not been swept up by the planets
because of the high inclination of their orbits, or
probably because their orbits are so nearly circular tha
do not cross the orbits of any of the planets.

gives indisputable evidences (Art. 219) radiated more energy than could have bee known source. The existence of hundr stars blazing in full glory also suggests lifetime of a sun is very long, for it is not pose that, if they endured only a compar so many of them would now have such gr view of these uncertainties it is not safe limit on the future duration of the sun, its final extinction may be.

If the sun cools off before something de they will revolve around it cold, lifeless, a it pursues its journey through the trackles If the radiation of the sun does not sens earth, and possibly some of the other pla to be suited for the abode of life until way destroyed. Whether or not the sun planets will be broken into fragments wh sufficiently near another star. Their ren dispersed among the revolving masses of system, to become in time parts of new the meteorites which now strike the earth of having once been in the interior of n dimensions, and Chamberlin has suggest be the remains of a family of planets a To such dizzy heights are we led in sober

The question of the purpose of all the the universe is one which ever arises in With sublime egotism men have usually a thing was created for their pleasure and was made to give them light by day, and myriads of stars to illuminate their w numberless plants and animals of fore sea were supposed to exist primarily f human race. But with the increase of clusion is seen to be absurd. How ir

nical forces and the
ate. Nothing could
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tral sun and a family

g the molecules would
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ese masses would acquire
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and fatal difficulties. In the
d repulsive forces would not
general revolution of a system
. His conclusion in this matter
e that the moment of momentum
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tatements by Kant, some writers
y supposing that there was hetero-
inal chaos with a predominance in
e planets now revolve. But with
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ties still remain. It is not at all
of such enormous extent the orbits
ose having motion in the dominant

...ngs. There is, indeed, ...history of the ...ould ... now be found ...al plan... of the system. This is ... impossible, ...s. This is seen that ...s he gave it, the condi- ... of the system should ... that if the postulates ...y, others still remain. ...ifficulties of a serious ...mutual attractions of ...ther into small nuclei. ... its mass if it should ...culty one might assume ... liquid or solid state, ... in the formation of ...raging process, their ...y one another, the ... the whole system, ...rder to avoid this ... Kant's ideas and to ...ss was rotating with ...was not in a gaseous ...s made, it is found ...oment of momen- ...00 times what it is ...um would remain ...be adopted. But ...al assumptions of ... a theory as hav- ... modified to this ...ed, viz., that of ... same direction,

... the densities and

ratios of the masses of the planets, the eccentricities of the planetary orbits and the origin of comets, the origin of satellites and the rotation of the planets, etc. He even claimed to have proved without observational evidence the existence of life on other planets. In spite of the keenness of his intellect and his remarkable powers of generalization, his theory has not had much influence on speculations in cosmogony, because it is marred by so many serious errors in the application of physical and dynamical laws.

262. The Hypothesis of Laplace. — The hypothesis of Laplace appeared near the end of a splendid popular work on astronomy which he published in 1796. He advanced it "with that distrust which everything ought to inspire that is not a result of observation or of calculation." How great an advance over Kant this one sentence indicates!



FIG. 162. — Laplace.

In outline, the hypothesis of Laplace was that originally the solar atmosphere (in later editions a nebulous envelope), in an intensely heated state, extended out beyond the orbit of the farthest planet; the whole mass rotated as a solid in the direction in which the planets now revolve; the dimensions of the solar atmosphere were maintained mostly by gaseous expansion of the highly heated vapors, and only slightly by the centrifugal acceleration due to the rotation; as the mass lost heat by radiation, it contracted under the mutual gravitation of its parts; simultaneously with its contraction, its rate of rotation necessarily increased because the moment of momentum remained constant; after the rotating mass had contracted to certain dimensions the cen-

trifugal acceleration at the equator equaled the attraction by the interior parts and an equatorial ring was left behind, the remainder continuing to contract; a ring was abandoned at the distance of each planet; a ring could scarcely have had absolute uniformity, and, separating at some point, it united at some other because of the mutual attractions of its parts and formed a planet; and, finally, the satellites were formed from rings which were left off by the contracting planets, Saturn's rings being the only examples still remaining.

The contraction theory of the sun's heat, which was developed by Helmholtz in 1854, fitted in very well with the Laplacian hypothesis and was considered as supporting it. Some objections to the Laplacian theory, however, began to appear. In 1873 Roche, the author of the theorem that a satellite would be broken up by tidal strains if its distance from its primary should become less than 2.44 radii of the latter, seriously undertook to modify the hypothesis of Laplace so as to relieve it of the difficulties with which it was beset. His modifications were for the most part improbable and do not in the least meet later objections. Kirkwood, an American astronomer, criticized the Laplacian hypothesis and pointed out that the direct rotation of the planets might be due to the effect of the sun's tides on them when they were expanded in the gaseous state. In 1884 Faye made very radical modifications of the hypothesis of Laplace for the purpose of avoiding the difficulties in which it was becoming involved. He supposed that the planets were formed in the depths of the solar nebula and that those nearer the sun are actually older than those which are more remote. About 1878 Darwin began his great work on the tides which he regarded as supplementing and strengthening the hypothesis of Laplace.

It is now generally recognized that the Laplacian hypothesis fails because it does not meet the most fundamental requirements of the problem. For example, the density of the hypothetical solar atmosphere must have varied in har-

mony with the laws of gases. With this distribution of density, which can be theoretically determined, and the rotation which is given by the revolution of the planets, it is an easy matter to compute the moment of momentum possessed by the hypothetical system when it extended out to the orbit of Neptune. It turns out to be more than 200 times that of the system at present. If the hypothesis of Laplace were correct, the two would be equal; the discrepancy is so enormous that the hypothesis must be radically wrong.

The details of the Laplacian hypothesis are subject to equally serious difficulties. For example, it would be impossible for successive rings to be left off. Kirkwood long ago pointed out that if instability in the equatorial zone once set in, it would persist, and Chamberlin has shown that the result would be a continuous disk of particles describing nearly circular orbits. Further, if a ring were left off, it could not even begin to condense into a planet because both gaseous expansion and the tidal forces due to the sun would more than offset the mutual gravitation of its parts. It has been seen how large and dense [1] a planet must be in order to hold an atmosphere; while the ring would be large, its density would be extremely low and it could not control the other elements. And it has been shown that even if a circular ring had in some way largely condensed into a planet, the process could not have completed itself. In order that it may gather up scattered materials, it is necessary that it shall be moving in considerably eccentric orbits.

[illegible] Laplacian hypothesis fails in the fundamental [illegible] of moment of momentum, as well as in a number of essential respects, it will be sufficient simply to [illegible] some of the phenomena which are obviously not [illegible] with it:

[illegible] not provide for the planetoids with their

[1] [illegible] power of a planet on an atmosphere is proportional to [illegible] density and radius.

interlacing orbits, some having high inclinations or eccentricities.

(2) It does not permit of the existence of an object having such an orbit as that of Eros, which reaches from near that of the earth out beyond that of Mars.

(3) It implies that a continuous disk of particles, such as that producing the zodiacal light, cannot exist.

(4) It does not anticipate the considerable eccentricity and inclination of Mercury's orbit.

(5) It does not agree with the fact that the terrestrial planets seem to be at least as old as the more remote ones.

(6) It does not permit of there being any retrograde satellites because the rings abandoned by a contracting nebula would necessarily all rotate in the same direction.[1]

(7) It implies that the rotation period of each planet shall be shorter than the shortest period of revolution of its satellites. This condition is not only violated in the case of the inner satellite of Mars, but the particles of the inner ring of Saturn revolve in half the period of the planet's rotation.

263. Tidal Forces. — The sun and moon generate tides in the oceans that cover the earth. Tides are raised also in the atmosphere and in the solid earth itself. Similarly, every celestial body raises tides in every other celestial body. The first problem which will be considered here will be the character of the tide-raising forces, and the second will be the effects of the tides on the rotations and revolution of the two bodies.

Consider the tide-raising effects of m on M, Fig. 163. For simplicity, consider the effects of m on P and P', two particles on the surface of M. The problem of the resolution of the forces is that which was treated in Art. 153. Let MA represent the acceleration of m on M in direction and amount. Then the acceleration of m on P and P' will be represented by PB and $P'B'$ respectively. The former is

[1] Attempts have been made, though not successfully, to avoid this difficulty by invoking tidal friction (Art. 264).

greater than MA because the acceleration varies inversely as the square of the distance, and Mm is greater than Pm. For a similar reason $P'B'$ is less than MA. Now resolve PB into two components, PC and PD, in such a way that PC shall be equal and parallel to MA. Similarly, resolve $P'B'$ into $P'C'$, equal and parallel to MA, and $P'D'$. Since PC and $P'C'$ are equal and parallel to MA, they have no tendency to displace P and P' respectively with respect to M. The remaining components, PD and $P'D'$, are the tide-raising accelerations.

Now consider the tide-raising forces all around M. They are as indicated in Fig. 94. The forces toward m are slightly

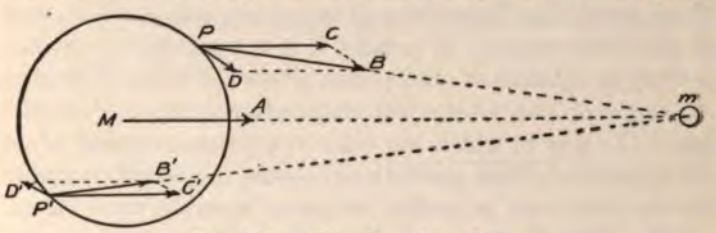


FIG. 163. — The tide-raising force.

greater than those in the opposite direction, while the compressional forces at 90° from these directions are half as great. It is clear from this figure that if M were not rotating and m were not revolving around it, there would be a tide on the side of M towards m, and a nearly equal tide on the side of M away from m (compare Art. 153). The motions of the bodies produce important modifications.

Suppose the rotation of M and the revolution of m are in the same direction and that the period of rotation of M is shorter than that of the revolution of m. This is the case in the earth-moon system. Under these circumstances the tides T_1 and T_2 are carried somewhat ahead of the line Mm, as represented in Fig. 164. The more nearly equal the rates of rotation of M and revolution of m, the more nearly will the tides T_1 and T_2 be in the line Mm.

Consider a point on the rotating body M. It will first pass the line Mm, and then somewhat later it will pass the tide T_1. The interval is the lag of the tide. In the case of the earth-moon system a meridian passes eastward across the moon (the moon seems to pass westward across the meridian), and somewhat later the meridian passes the tidal cone and has high tide. The problem is enormously complicated in the case of the earth by the addition of the tides due to the sun, by the varying distances of the moon and sun north or south of the celestial equator, by their changing distances from the earth, and especially by the irregular contours of the continents and the varying depths of the oceans. These modifying factors are so numerous and in some cases so poorly known that at present it is not possible to predict entirely in advance of observation either the times or heights of the tides; but, after a few observational data have established the way in which the tides at a station depend upon the unknown factors, predictions become thoroughly reliable, for the tides vary in perfect harmony with the tidal forces.

264. Tidal Evolution. — The tides are not fixed on the surface of M, Fig. 164, unless the period of its rotation equals the period of revolution of m. When the periods are unequal so that the tides move around the rotating body, some energy is changed to heat by friction. This energy comes from the kinetic and potential energies of the system; and, in accordance with the laws of dynamics, the transformation of energy takes place in such a way that the total moment of momentum of the system remains unchanged. Of course, in general there will be tides on both of the mutually attracting bodies.

The character of the transformation of energy that takes place under tidal friction depends upon the dynamical properties of the system. Suppose that the motions of rotation and revolution are in the same direction and that the period of M is shorter than that of m. It can be shown that under these circumstances the periods of both M and m

and their distance apart are increased. The reason that the period of rotation of M is increased is that m has a component of attraction back on both T_1 and T_2, Fig. 164, as can be shown by resolving the forces as they were resolved in Fig. 163. If m pulls T_1 and T_2 backward, it follows from the reaction of forces that T_1 and T_2 pull m forward. The result of a forward component on m is to increase the size of its orbit and to lengthen its period.

If m is near M, the effect of the tides on the period of revolution of m is greater than their effect on the period of rotation of M. If the bodies are far apart, the result is the opposite.

Suppose the two bodies are initially close together and that the period of rotation of M is only a little shorter than the

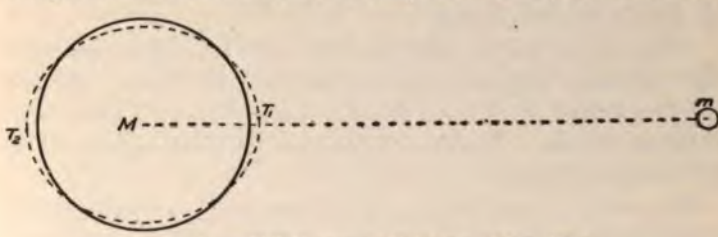


FIG. 164. — Tidal cones and the lag of the tides.

period of revolution of m. The friction of the tides will lengthen both periods and increase the difference between them. If nothing else interferes, this will continue until a certain distance between the bodies has been reached. After that, the effect on the period of rotation of M will be greater than that on the period of revolution of m. Consequently, although both periods will continue to increase in length, they will approach equality. Eventually, the periods of rotation and revolution will be equal, the tides will remain fixed on M, and there will be no further tidal friction or tidal evolution.

The most important case from a practical point of view has been considered, but there are two others. In the first the bodies move in the same direction, but the period of

rotation of M is longer than that of revolution of m. Under these circumstances both periods are decreased, the relative amounts depending on the distance of the bodies from each other. If the bodies are initially far apart, the effect will be greater on the period of rotation of M than on the period of revolution of m, and the two periods will approach equality. But if the bodies are near together, the effect will be relatively greater on the period of m, the periods will not approach equality, and the bodies will ultimately collide. In the second case the rotation of M is in the direction opposite to that of the revolution of m. Under these circumstances M rotates faster and faster, the distance of m continually decreases, and the inevitable outcome is the collision and union of the two bodies.

The rate at which tidal friction takes place depends upon the physical properties of the bodies. If they are perfect fluids so that there is no degeneration of energy, there is no tidal evolution. Likewise if they are perfectly elastic, there is no tidal friction.

The rate of tidal friction also depends upon the difference in the periods of the two bodies. If the difference between the periods is small, the tides T_1 and T_2, Fig. 164, are almost in the line Mm, and it is obvious that the backward components are small and the rate of tidal friction is very slow. Suppose the periods are approaching equality. The smaller their difference the slower is their rate of change, and they never become exactly equal but approach equality as the time becomes infinitely great.

265. Effects of the Tides on the Motions of the Moon. — The most striking thing in the earth-moon system is that the moon's periods of rotation and revolution are equal. It is extremely improbable that this unique relation is accidental. The only explanation of it heretofore advanced is that the moon's period of rotation has been brought into equality with its period of revolution by the tides generated in it by the earth.

The tidal force exerted by the earth on the moon is about 20 times the tidal force exerted by the moon on the earth. The amount of tidal friction is proportional to the square of the tidal force. Therefore, if the physical properties of the earth and moon were the same and if their periods of rotation were equal, the effectiveness of the tides generated by the earth on the moon in changing the moment of momentum of the moon would be 400 times that of the tides generated by the moon on the earth in changing the moment of momentum of the earth. Since the moment of momentum of a body is proportional to the product of its mass and the square of its radius, a given change in the moment of momentum of the moon alters its rate of rotation 1200 times as much as the same change in moment of momentum alters the rate of rotation of the earth. Consequently, taking the two factors together, if the earth and moon were physically alike and had the same period of rotation, tidal friction would change the period of rotation of the moon $400 \times 1200 = 480{,}000$ times as fast as it would change the period of rotation of the earth.

The results which have been obtained seem to be very favorable to the theory that the tides have caused the moon to present one side toward the earth, but some serious difficulties remain. It can be shown that, considering the tidal interactions of the earth and moon and the effect of the sun's tides on the moon, the present condition of the earth-moon system is not one of equilibrium. The tides raised by the earth on the moon have no effect under present circumstances on the rotation and revolution of the moon. The tides raised by the moon on the earth increase the length of the month but do not affect the rotation of the moon. The tides raised by the sun on the moon increase the moon's period of rotation but do not affect its revolution. Consequently the moon's periods of rotation and revolution are both increasing, and it is infinitely improbable that all the factors on which these effects depend are so related that

they are exactly equal. Even if they were equal they would become unequal with a changed distance moon from the earth. That is, the present is not of equilibrium, and the consideration of the remove the difficulties. It seems probable from thought that some influence so far not considered the moon always to present the same face toward

266. Effects of the Tides on the Motions of The theory of the tidal evolution of the earth-on the basis of certain assumptions regarding condition of the earth, was elaborated by Sir G in a splendid series of investigations. While of Michelson and Gale (Art. 25) proves that bi are not satisfied, at least at the present time sequence of events which he worked out is in

Since the tides are increasing the length day and the month, both of these periods shorter and the moon was nearer the earth. of his assumptions, Darwin traced the day ba only four or five of our present hours. At moon was revolving close to the earth in a equally short. This led him to the conclusi earlier stage the earth and moon were one bo divided into two parts because of the rapid r combined mass, and that they have attained state as a consequence of tidal friction. The ing leads to the conclusion that in the future tinue to separate and that the day will conti in length.

The critical question is whether the ph

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pothesis fail to meet the

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oon, what is the magnitude of
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T_1 tend to decrease the rate of

of the earth is constant and that
ead of the place it would occupy
ant. How long would be required
ut?



Photographed by Barnard at the Yerkes Observatory, August 27, 1905.

r of them revealed by a telescope will
space it brings within visual range.
he stars are less densely distributed at
ny direction, then the number of faint
that direction will fall short of being
space penetrated by the instrument.
important to find the number of stars of
lown to the limits of range of the most
es.

what the apparent distribution in magnitude
rs of every actual size and luminosity were
rmly throughout space. Take a large enough
t accidental groupings will not sensibly affect
For example, suppose there are 5000 stars in
agnitudes and compute the number there should
the hypothesis, in the first seven magnitudes.
magnitude stars are 2.512 ··· times as bright
enth-magnitude stars. Since the amount of light
from stars of given absolute brightness varies in-
s the squares of their distances, it follows that stars
eventh magnitude are $\sqrt{2.512} \cdots = 1.585 \cdots$ times as
as corresponding stars of the sixth magnitude.
fore the volume occupied by stars out to the seventh
itude, inclusive, is $(1.585 \cdots)^3 = 3.98 \cdots$ times that
pied by the first six magnitudes. Hence, if the stars
e uniformly distributed and the light of the remote ones
re in no way obstructed, there would be 3.98 ··· times as
any stars in the first seven magnitudes as in the first six
agnitudes, or nearly 20,000 stars. The ratio is the same
for the total number of stars up to any two successive
magnitudes because the particular magnitudes do not
enter into its computation. And it can be shown easily
that the ratio of the number of stars of any magnitude to the
number of the next magnitude brighter is also 3.98 ···.

It remains to examine the results furnished by the obser-
vations. The stars are so extremely numerous that only a

they will henceforth fit into a large body of organized facts. From now on the romance and excitement of astronomical adventure will be largely furnished by the explorations of the sidereal universe. Astronomers have become accustomed to the fact that the sun is a million times as large as the earth, and familiarity has dulled their amazement at its terrific activities; from now on they must deal with millions of stars, some of them much larger and thousands of times more luminous than the sun. They have measured and at least partially grasped the enormous dimensions of the solar system; from now on they must conceive of and deal with distances millions of times as great. They have observed the differences in characteristics exhibited by eight planets; from now on they will be face to face with the infinite diversity presented by the stars. They have definitely accepted the doctrine that the solar system has undergone a great evolution whose details are yet much in doubt; the corresponding question for hundreds of millions of other systems is looming up more indistinctly through the fogs of uncertainties which still surround them. It might be supposed that astronomers would be tempted to lay down the arms of their understanding before the transcendental and appallingly difficult problems presented by the sidereal system. Instead, with all the weapons at their command, they are making more vigorous, persistent, and successful attacks than ever before. Astronomers of all the leading countries are united and coöperate in this campaign; they employ telescopes of many kinds, spectroscopes, photographic plates, measuring machines, and powerful mathematical processes in their attempts to penetrate the unknown.

269. The Number of Stars of Various Magnitudes. — The simplest and most easily determined thing about the stars is their number. Of course the number that can be seen depends upon the power of the instrument with which the observations are made. If the stars extend infinitely in every direction with approximately equal distances from

[illegible]

[illegible] space [illegible]

[illegible] to the [illegible]

[illegible] the apparent [illegible]

[illegible] very [illegible]

[illegible] throughout space [illegible]

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[illegible] suppose [illegible]

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no absorbing material, there would be no limit, except for the mutual eclipsing of the stars, to the amount of light received from all of them. The sky would be everywhere ablaze with the average brightness of a star, perhaps equal to that of the sun. The stars in one hemisphere would give us more than 90,000 times as much light as the sun, but actually the sun gives us 15,000,000 times as much light as all the stars together. Therefore, unless much light is absorbed, the hypothesis of uniform distribution of the stars to infinity is radically false.

Is it necessary, therefore, to conclude that the number of stars is limited and that they occupy only a finite part of space? By no means; simply that they cannot be distributed with approximate uniformity throughout infinite space. It was pointed out by Lambert long ago that, just as the solar system is a single unit in a galaxy of several hundred million stars, so the Galaxy may be but a single one out of an enormous number of galaxies separated by distances which are very great in comparison with their dimensions, and that these galaxies may form larger units, or supergalaxies, and so on without limit. There is nothing in such an organization which is inconsistent with the facts established by observation, for it is possible to build up infinite systems of stars in this way which would give us only a finite amount of light. Hence the conclusion to be adopted is that the sun is in the midst of an aggregation of at least several hundred millions of stars which form a sort of system, and that beyond and far distant from this system there may be other somewhat similar systems in great numbers, which may be units in larger systems, and so on without limit.

It is conceivable that the ether is not infinitely extensive, but that it surrounds the stars of the sidereal system (and other stellar systems if there are such) as the atmospheres surround the planets. Light could not come to us from beyond its borders, however many stars might exist there, as sound cannot come to the earth from other bodies beyond

TABLE XV

ZONE	I	II	III	IV	V	VI	VII	VIII
Galactic Latitude / MAG.	0 to ± 10°	± 10° to ± 20°	± 20° to ± 30°	± 30° to ± 40°	± 40° to ± 50°	± 50° to ± 60°	± 60° to ± 70°	± 70° to ± 90°
1 to 5	0.27	0.23	0.15	0.11	0.11	0.11	0.13	0.13
6	0.7	0.7	0.5	0.4	0.3	0.3	0.3	0.3
7	2.6	2.3	1.8	1.5	1.2	1.1	1.1	1.1
8	8.0	7.0	6.1	4.8	3.8	3.4	3.2	3.1
9	24	21	18	14	10	10	9	8
10	62	55	50	38	28	26	22	20
11	157	135	123	93	63	62	52	47
12	363	311	280	199	136	141	115	100
13	798	658	569	409	276	295	240	205
14	1,642	1,354	1,142	770	531	572	482	392
15	3,253	2,650	2,080	1,390	940	1,050	916	773
16	6,150	4,936	3,680	2,340	1,680	1,830	1,630	1,400
17	11,540	9,170	6,350	3,980	2,870	3,100	2,990	2,610
Total	24,000	19,300	14,300	9,240	6,540	7,090	6,460	5,560

Three things follow from this table: (*a*) Stars of all magnitudes down to the seventeenth are more numerous in the plane of the Milky Way than near its poles. Since the only reasonable supposition is that the nearer stars are distributed more or less uniformly with no special relations to the Milky Way, it follows from the fact the bright stars are condensed near the Milky Way that some of them are very distant. That is, the stars differ greatly in absolute luminosity, a conclusion confirmed by direct evidence. (*b*) The decrease in the number of stars is on the average gradual from the Milky Way to its poles, showing that the sun is actually in the midst of the clouds of stars on which the table is based. (*c*) The relative condensation in the plane of the Milky Way is greater, the fainter the stars. This proves that the stars are not only much more numerous near the plane of the Milky Way, but also that they extend to much greater distances in this plane than in the direction

can be seen with the unaided eye shows that they are co
siderably more numerous in and near the Milky Way tha
elsewhere. When those stars which can be seen only wit
the help of a telescope are included, the condensation towar
the Milky Way is still more pronounced.

Precise numbers for all the stars are known only to th
ninth magnitude; but the star counts of the Herschels, an
especially the work of Chapman and Melotte, go muc
further and give what are very probably approximatel
correct results down to the seventeenth magnitude. Sin
the stars are apparently condensed toward the Milky Wa
it is natural to use its plane as the fundamental plane
reference. According to E. C. Pickering the north pole
the Galaxy is in right ascension 190° and its declination
+ 28°. The Milky Way is very irregular in outline, and
is difficult to locate its center; but its median line is possib
not quite a great circle, from which it follows that the
is somewhat out of the plane near which the stars are co
gregated.

Let the center of the Milky Way be the circle from whi
galactic latitudes are counted. Chapman and
divided the sky up into eight zones, the first includi
belt of galactic latitude 0° to ± 10°, the second the two be

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join and reach on into Cassiopeia, where the description of the Milky Way began.

It is obvious that the stars do not form any simple system. It seems probable that the Galaxy is composed of a large



FIG. 167. — The region of Rho Ophiuchi. *Photographed by Barnard.*

number of star clouds, each with peculiarities of its own, but having relations to the whole mass of stars. Since the Milky Way is roughly in the form of a great discus, or "grindstone" as Herschel called it, the prevailing motions must be in its plane in order to have preserved its shape.

This does not mean that the relative velocities would need to be great enough to be easily observed; they would, in fact, be very slight as seen from the enormous distances separating the stars from the earth.

XXII. QUESTIONS

1. Prove that the magnitudes of stars of equal absolute brightness are proportional to the logarithms of their distances.

2. Prove that, under the hypothesis of the second paragraph of Art. 269, the ratio of the number of stars of any magnitude to the number of the next magnitude brighter is 3.98.

3. If there are 2000 stars of magnitude 5 to 6, and if the ratio for successive magnitudes were 3.98, how many stars would there be of magnitude 16 to 17?

4. Prove that the effectiveness of a given mass in screening off light is inversely proportional to the radius of the particles into which it is divided.

5. Show in detail how it follows from Table XV and the assumption under (*a*) that some of the bright stars are very distant. How many of the 20 first-magnitude stars have parallaxes greater than 0″.2 (see Table XVI)?

6. At what distance, expressed in parsecs (Art. 272), would the sun be a first-magnitude star? A sixth-magnitude star? If Canopus has a parallax of 0″.005, how does its absolute brightness compare with that of the sun?

7. Prove that the area of one hemisphere of the sky is 92,000 times the apparent area of the sun.

8. Prove in detail that conclusion (*b*) of Art. 270 follows from Table XV.

9. At what time of the year does the portion of the Milky Way which is divided by a longitudinal rift pass the meridian at 8 P.M.? If possible, observe it.

10. Draw a diagram and show that the fact that the central line of the Milky Way is not quite a great circle proves that the solar system is not in the center of the disk of stars of which the Milky Way is composed.

11. The fact that the Milky Way is very oblate implies that it has large moment of momentum about an axis perpendicular to its plane. What inference do you draw respecting the general motions of stars in exactly opposite parts of the Milky Way?

12. If all visible objects belong to the Galaxy, is it possible to prove the rotation of the Milky Way by observations of the stars?

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the Milky Way began.

It is obvious that the stars do not fo
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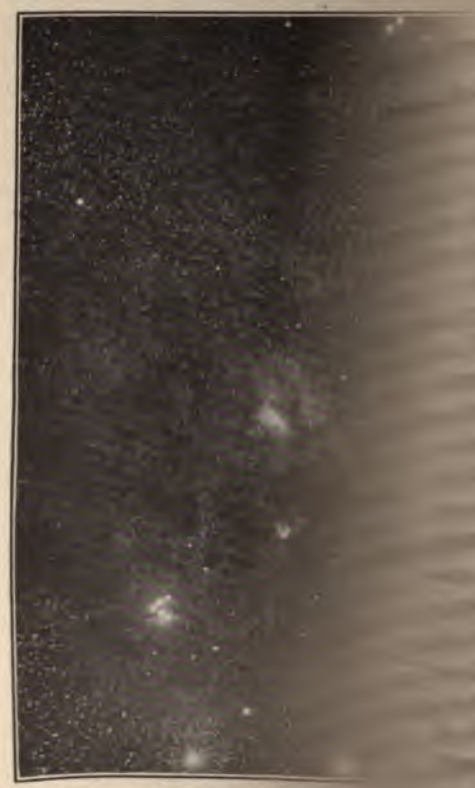


Fig. 167. — The region of Rho

number of star clouds, each
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Stars

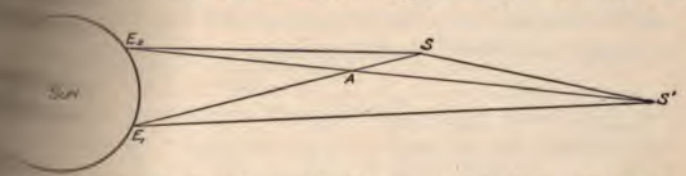
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rect means of determining the parallax of a earing, at various times of the year, its appar- with the positions of more distant stars. Let S, resent a star whose parallax is required, and S' distant star. When the earth is at E_1 the ance between them is $\angle SE_1S'$; when the earth is SE_2S'. The parallax of S is $\angle E_1SE_2$; the S' is $E_1S'E_2$, which will be negligible if S' is suffi- mote. It easily follows from the geometry of the the parallax of S minus the parallax of S' equals rence of the measured angles SE_1S' and SE_2S'.



168. — Determination of parallax from apparent changes in relative positions of stars.

nce, if the parallax of S' is inappreciable, the parallax of can be found.

In practice the position of S is measured with respect to a number of comparison stars. At present the work is done almost entirely by photography. Plates of a star and the surrounding region are secured at different times of the year, and the distances between the stars are measured under a microscope on a machine designed for the purpose. The scale of the photograph is proportional to the focal length of the telescope, and consequently for this purpose only large and excellent instruments are of value.

With present means of measurement, a parallax of 0″.02 or less cannot be determined with sufficient accuracy to be of much value; in fact, the probable error in one of 0″.05 is large. The great distances of the stars can be inferred

13. What observational evidence di[illegible] known whose parallaxes there are infinitely many galaxies dis[illegible] uniformity, but separated from one a[illegible] are enormous compared to their dimens[illegible]

II. Distances and Motion[illegible]

272. Direct Parallaxes of the N[illegible] the proofs that the earth revolves ar[illegible] apparent directions of the nearest s[illegible] tion of the earth in its orbit (Art[illegible] direction of a star as seen from tw[illegible] each other by the mean distance fr[illegible] is the parallax of the star; or, in o[illegible] of the star is the angle subtended by[illegible] earth's orbit as seen from the star (I[illegible] were one second of arc, the distan[illegible] 206,265 times [1] the mean distance fr[illegible] This distance, which is a very conv[illegible] the distances of the stars, is called t[illegible] practical purposes it may be taken[illegible] nomical units, or 20,000,000,000,000 [illegible] that light travels in about 3.3 years.

The stars are so remote that the pr[illegible] parallaxes is one of great practical[illegible] tauri, the nearest known star, has a[illegible] That is, its difference in direction as[illegible] the earth's orbit, separated by the [illegible] to the sun, is the same as the differ[illegible] object at the distance of 10.8 miles w[illegible] eye and then with the other. Not [illegible] the apparent position of a star very[illegible] ferent parts of the earth's orbit, bu[illegible] only from observations separated by[illegible]

[1] This number is the number of seconds in a[illegible] its radius in length.

[illegible] are 0″.2 or greater [illegible] exceeding about 25 per [illegible]. There are at present [illegible] faint to be seen with- [illegible] in Table XVI. When [illegible] itude has been deter- [illegible] dates, or its luminosity, [illegible] uted. The luminosity [illegible] in the fifth column.

Luminosity (Sun=1)	Mass (Sun=1)	Velocity (Mi. per Sec.)
2.0	1.9	20
0.039	?	35+
48.0	3.4	11
0.50	?	20
0.7	1.3	12
0.007	?	170
0.79	?	14
0.10	?	63
0.019	?	72
0.006	?	23+
0.25	?	54
0.010	?	30+
0.004	?	14+
0.005	?	11+
123	?	22
1.4	1.0	20
0.3	?	30
0.011	?	66+
1.808	?	45+

[illegible] with our sun occupy a [illegible] if they were uniformly [illegible] between adjacent [illegible] 12.2 light years. In [illegible] in the list are far

visibility without optical aid, it is reason-
there may be a considerable number of
arsecs of the sun which are as yet undis-

supposed that attempts have been made
parallaxes of all stars brighter than the
sixth, magnitude. The process is exces-
and only those stars are selected which are
within measurable distance, or which are
interest for other reasons. A star with a
cross the line of sight will apparently move
ver it is to the observer. Consequently,
ll be nearest on the average whose *proper*
y are called, are greatest. As a rule only those
mined for parallax which have been found to
oper motions.

hypotheses that the stars are uniformly dis-
ughout the space occupied by the Galaxy and
sity is the same as it is in the vicinity of the
tent of the stellar universe can be computed.
space occupied by the stars is spherical in shape
ere are 500,000,000 of them. Then it turns out
the hypotheses adopted, the radius of this sphere
es, or 5000 light-years. Since the Galaxy is very
ened, the distance to its poles is probably only a
ed parsecs while the borders of its periphery are
several thousand parsecs from its center.

y interesting and important conclusion follows from
VI, and that is the luminosities of the stars
rmously. For example, Sirius radiates 12,000
much light as OA(N.) 17,415. These differences in
y may be due to the fact that some stars are larger
hers, or at least partly to the fact that some are
lly more brilliant than others. Probably both
re important. Some stars are certainly much more
than others, and the table gives examples of stars

from the fact that only about 100 are known who come within the wider of these limits.

The distances of stars whose parallaxes are 0″.2 can be measured with an error not exceeding ab cent of the quantity to be determined. There are 19 such stars known, 9 of which are too faint to be s out optical aid. These stars are given in Table XV the distance of a star of known magnitude has be mined, the total amount of light it radiates, or its lu as compared with the sun can be computed. The lu of each of the nineteen stars is given in the fifth col

TABLE XVI

STAR	MAGNITUDE	PARALLAX	DISTANCE (PARSECS)	LUMINOSITY (SUN = 1)	MASS (SUN = 1)	V (M
		″				
α Centauri . .	0.3	0.76	1.32	2.0	1.9	
Lalande 21,185 .	7.6	0.40	2.50	0.009	?	
Sirius	−1.6	0.38	2.63	48.0	3.4	
τ Ceti	3.6	0.33	3.00	0.50	?	
Procyon . . .	0.5	0.32	3.13	9.7	1.3	
C. Z. 5^h 243 . .	8.3	0.32	3.13	0.007	?	
ε Eridani . . .	3.3	0.31	3.23	0.79	?	
61 Cygni . . .	5.6	0.31	3.23	0.10	?	
Lacaille 9352 .	7.4	0.29	3.45	0.019	?	
Pos. Med. 2164 .	8.8	0.29	3.45	0.006	?	
ε Indi	4.7	0.28	3.57	0.25	?	
Groombridge 34	8.2	0.28	3.57	0.010	?	
OA(N.) 17,415 .	9.3	0.27	3.70	0.004	?	
Krueger 60 . .	9.2	0.26	3.85	0.005	?	
Altair	0.9	0.24	4.17	12.3	?	
η Cassiopeiæ .	3.6	0.20	5.00	1.4	1.0	
σ Draconis . .	4.8	0.20	5.00	0.5	?	
Lalande 21,258 .	8.9	0.20	5.00	0.011	?	
OA(N.) 11,677 .	9.2	0.20	5.00	0.008	?	

The 19 stars of Table XVI together with our sun o sphere whose radius is 5 parsecs. If they were u distributed in this space, the distance between a stars would be about 3.7 parsecs, or 12.2 light ye view of the fact that a number of stars in the list

whose masses differ very much less than their
For example, while the mass of Sirius is only 2
of the sun, its luminosity is 48 times as great.
double star and presents in its own systen
remarkable contrast. The mass of the brigh
is approximately twice that of the fainter or
nosity it is at least 5000 times greater. Ther
such as Rigel and Canopus, which, though th
that no evidence of their having measurabl
been found, shine with the greatest brillian
nosity must be at least several thousand tim
In fact, the average luminosity of the st
unaided eye probably exceeds that of the
dred fold. It must not be assumed fr
luminosity of the sun is below the averag
in luminosity by only five of the 19 stars

In order to determine the velocity of a
along and across the line of sight must be
motions of all the stars in Table XVI
radial velocities of six of them are unk
a plus sign is placed after the numbe
because the radial component is not kn
the table that the less luminous st
higher velocities than the brighter one
of those five stars whose luminosities
miles per second, while the average
luminosities are less than 0.01 that o
50 miles per second. Since the m
almost certainly the more massive,
massive stars move more slowly tha

One may inquire to what exten
conclusions based on only 19 sta
hundreds of millions the number is
the conclusions which have been sta
by the evidence furnished by the
having smaller and less accurately

The hypotheses on which this discussion ha
are not exactly fulfilled, and the necessary mo
the proposed method must now be considered.

274. Motion of the Sun with Respect to the St
the stars are in motion, it is reasonable to
the sun is moving among them. Such was
the case by Sir William Herschel more than a
He proved by observations extending over ma
the apparent distances between the stars i
tion of the constellation Hercules are increa
average, and that they are decreasing in the exa
part of the sky. He interpreted this as
the sun is moving toward the constellation H
it is obvious that this would explain the ob
nomena; for, as objects are approached, th
larger angles. While Herschel's observatio
direction of motion of the sun, they did
speed, which could be found by this method
distances of the stars were known. Since the
only a few stars can be measured directly, there
of determining the motion of the sun in this w
considerable degree of accuracy.

The spectroscope has been used to determi
direction of the sun's motion and also the rate
moves. Instead of finding as many stars app
receding in every part of the sky, as was assume
cussion in Art. 273, it has been found that the
direction of the constellation Hercules on the
relatively approaching the sun, while those in t
direction are relatively receding. This means
respect to the stars which were observed the sun
toward Hercules.

The best determination of the direction of the su
from proper motions of the stars is by Lewis Boss,
his discussion on the 6188 stars in his catalogue.
spectroscopic determination is by W. W. Cam

proper motion

cept the sun are
problem. As a
spect to one an-
speeds, and the
motion and also
e system. Since
is in general un-
motions of many,
the motion of the
For any class of
ular to the direc-
the average proper
will depend only

taken up about 20
ho pursued it with
of other astronomers
to the subject. It
of work which con-
place, the proper
are obtained from
position separated
longer the intervals
ons determined. In
fundamental impor-
the sun with respect
ars may be moving as
t. 278), it follows that
e motion of the sun
whose distances are
At present the radial
xth magnitude can be
ires, and the practical
th magnitude. On the

the stars down to magnitude 5.5 by t
article. The brighter stars were not suffic
give very reliable results. He found that
of stars of magnitudes 4.51 to 5.50 is 0″.0
to a distance of 80 parsecs. This volu
that occupied by the 20 nearest stars, an
uniformly distributed throughout it, the
them down to magnitude 5.50 would be
much in excess of the number actually ob

275. Distances of the Stars from the Mo

The parallaxes of only a comparatively sma
can be measured directly because their dist
mously great compared to the diameter of
If the orbit of the earth were as large as tha
problem would be much easier because of th
which could be used. But the sun's motio
afford an indefinitely large base line in statis
as will now be shown.

Suppose first that all of the stars of the ob
universe except the sun are relatively at res
of the sun among them will give them an ap
ment, or proper motion, in the direction opp
which it is moving. The farther a star is a

other hand, the determination of the pr
many magnitudes fainter offers no obse

**276. Kapteyn's Results Regarding t
Stars.** — As will be seen in Art. 295, mo
two principal spectral types. Type I, (
Vega are conspicuous examples, are whi
Their spectra are characterized by abso
hydrogen in their atmospheres. They ar
probably always of large mass. Type II
stars, of which the sun, Capella, and Arctu
The atmospheres of these stars contain ma

Kapteyn derived formulæ giving the m
all stars of each magnitude, and also the n
stars of each spectral type separately. T
Kapteyn's results transformed from paralla
using Campbell's more recent determinatio
motion of the sun.

TABLE XVII

DISTANCES IN PARSECS[1]

MAGNITUDE	ALL STARS	SPECTRAL TYPE I
1	24.2	39.4
2	31.0	50.5
3	39.7	64.7
4	50.9	82.9
5	65.3	106.3
6	83.7	136.3
7	107.3	174.7
8	137.5	224.0
9	176.3	287.2
10	226.1	368.3
11	289.8	472.1
12	371.6	605.3
13	476.4	776.0
14	610.8	994.9
15	783.0	1275.5

[1] One parsec equals 200,000 astronomical units, or 20,000,000,000,000 miles.

be suspected of being associated with the others except for the equality of their motions. For example, Sirius belongs to a group which includes five of the stars in the Big Dipper.

The best-known group of stars of the type under consideration comprises part of the Hyades cluster, in the constellation Taurus, and some neighboring stars scattered over an area about 15° in diameter. This group, which includes 39 known stars, was exhaustively discussed by Lewis Boss. The stars, in their proper motions, all seem to move along the arcs of great circles. Boss found that the great circles of all the stars of the Taurus stream intersect in a common point whose right ascension and declination are, for the position of the equinox in 1875, 6 h. 7.2 m. and + 6° 56′. It can be shown that this means that the stars of the group are moving in lines parallel to the line from the observer to the point of intersection of the circles. That is, their direction of motion is defined in this way, and since the stars cover a considerable area in the sky the point toward which they are moving is very well determined.

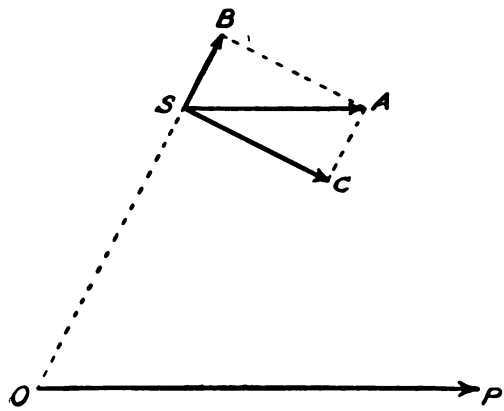


FIG. 169. — Components of motion in moving groups of stars.

It will now be shown that if, in addition to the data already in hand, the radial velocity of one of the stars of the group can be obtained, then the actual motions, the distances, and the luminosities of all of them can be determined. Let O, Fig. 169, be the position of the observer and OP the direction of motion of the stars of the group. Let S be one of the

stars which is moving in the known direction SA with unknown speed. Suppose the component SB is measur by the spectroscope. Then, since the angle ASB, whic equals the angle POS, is known, the whole component SA and the proper-motion component SC is found and the proper That is, the actual distance SC was already known. There- motion to which it gives rise can be computed. Since all the stars fore the distance OS can be computed from their respective of the group must have the same total motion SA, for other- wise they would not remain long associated, the distances of all the members can be determined advantageous to proper motions. Of course, it is practically measure the radial velocities of many, or all, of the members of the group. When the distance of a star of known magni- tude has been found, its absolute luminosity can be com- puted.

By these methods Boss found that the Taurus group is a globular cluster whose center is distant about 40 parsecs from the earth. Since its apparent diameter is about 15°, its actual diameter is about 10 parsecs. There is a slight con- densation toward the center of the cluster, but in the group as a whole the star density is only a little greater than it is in the vicinity of the sun. The distances between the stars of the group are so great that foreign stars could pass through it without disturbing their motions appreciably. In fact, in the course of the cluster it certainly sweeps past the sun there are probably several strangers now Boss found that 800,000 years ago its present distance and its apparent size was present. In 65,000,000 years it will be will appear from the earth to be a of a degree in diameter, made up of stars magnitude and fainter.

The stars of the Taurus cluster are much g lower than the sun. The lumino brightest are from five to ten times

while the largest are 100 times greater in
than our own luminary. Their masses a
greater than that of the sun.

The Ursa Major group of 13 stars is
system. It is in the form of a disk whos
4 or 5 parsecs while its diameter is 50
tances of the members of this group from
2.6 parsecs, in the case of Sirius, to 22 pars
the Big Dipper, and over 40 parsecs in
Aurigæ. The luminosities of the stars va
than 400 times that of the sun.

There is another fairly well-established
which was discovered almost simultaneo
Benjamin Boss, and Eddington. There
probable groups in which the proper mo
that the results have not been establishe
tion. In a universe of many stars it is in
should be many accidental parallelisms
motion. Stars are at present regarded a
group only if there is something quite dist
positions or motions.

278. Star-Streams. — In 1904 Kaptey
important discovery respecting the mo
He found that, instead of moving at ra
stars belong to two great streams having
tions of motion. Stars in all parts of th
tudes so far as the proper motions are
spectral types, partake of these motion
do not seem to be local, so to speak, as
the groups considered in Art. 277. Ye
too far to conclude that all the stars in th
up the Milky Way belong to these stream
was based on only a few thousands of
hundreds of millions in the sky. It see
Galaxy is made up of a great many of th
is, in fact, some reason to believe that

the period of the earth's revolution around the

The first question that springs to the mind is stars travel in sensibly fixed and closed orbits sir of the planets, or move on indefinitely througho occupied by the stars without ever retracing their paths. Since observations cannot at pr this question, the reply must be based on dynami tions. There is clearly no central mass among there is no center about which they seem to b with anything approaching symmetry. Mo motions give no hint that they are moving, even around some central mass or point.

The conclusion is inevitable that the stars d or less irregular paths, in the course of time prob ing into all parts of the sidereal system. In fac was likened by Kelvin to a great gas in which respond to the molecules. When they are fa mutual attractions are inappreciable, just as not interfere with the motions of one another times of collisions. If two stars should collide probably coalesce, the heat generated by their i ing them into the nebulous state. This would ferent from an elastic rebound of molecules. B

a velocity of only 0.00007 of an inch per second. Only after 900,000,000 years at the present distance would the relative velocity of the two amount to one mile per second. Long before such an immense time shall have elapsed the sun and Sirius will be far separated in space.

Now consider a group of stars, such as the cluster in Taurus, traveling through the stellar system. So far as their mutual interactions on one another are concerned the result is the same as though they were not moving with respect to the other stars. In their motion through space they are subject as a whole to the changing attractions of the other stars, and individually to possible close approaches. These factors may be considered separately.

The Taurus cluster consists of 39 (possibly more) stars which occupy a space whose diameter is roughly 10 parsecs. From the high luminosity of the individual members of the group it is reasonable to suppose that they have large masses, and it will be supposed that they average 10 times the sun in mass. It will be assumed that their motions are such that they are neither simply falling together nor scattering more widely in space, and that they are distributed uniformly throughout the volume which they occupy. That is, it is assumed that there is a balance (speaking roughly) between the gravitational forces among them and the centrifugal forces due to their relative motions. With these data and assumptions their maximum velocities with respect to the center of gravity of the group, and the time required for one of them to move from one border of the group to the opposite, can be computed.

It is found that the velocities of the stars of the group with respect to their center of gravity will always be less than 0.4 of a mile per second, and this maximum will be approached only very infrequently. If their masses are comparable to that of the sun instead of being 10 times as great, the velocities relative to their center of mass will always be less than 0.13 of a mile per second. Consequently, the internal motions

ing simply a much larger sys-
from all other systems, it will
metrical form. Its irregularities
that its age is not indefinitely
necessary conclusion if there were
haps even probability, of the exist-
ond our own near which, or through
intervals of time of a higher order
so far considered. These families of
still larger systems, and so on with-
it is impossible to conclude from the
tar clouds or galaxies that they have
duration. It should be added at once
ers believe, chiefly on the basis of the
nergy of the stars, that they have not
te time.

been possible to answer the more ambi-
ich have been raised, there remain others
thout interest. For example, suppose that
whole region occupied by the stars they are
they are near the sun; that is, that there are
phere whose radius is 5 parsecs. Suppose,
there is equilibrium between the attractive and
ces. So far as these assumptions approximate
ere is a relation between the dimensions of the
system and the mean velocity of stars at its
the velocities depend upon the star density and
of the region which they occupy. Inasmuch as
nsity in the neighborhood of the sun and the
of the stars have been determined by observa-
extent of the whole system can be computed.
lar system, which is far from the borders of the
will be supposed to be approximately at its center.
n velocity of the stars near the sun is about 22 miles
ond. This fact and the assumptions which have been
imply that the radius of the Galaxy is about 1100

considerable fraction of this distance the attra
great mass of stars in the Galaxy will have radi
and possibly reversed, its motion.

While the stars of the cluster pass close to oth
after very long intervals, they are continuall
slight disturbing forces which affect them s
equally. This results in a slight tendency t
members of the group. One might be tempte
from the fact that it is still very coherent that
be counted in hundreds of millions of years
But it is impossible to determine how many
longing to it have been torn from it by near
other stars, or how many of the smaller origi
been thrown to its borders by its internal in
then removed by the differential attracti
bodies, or how much more condensed it may
been. In short, no certain conclusions respe
one of these moving clusters can be drawn f
ties of the motion of their members at prese

It is now possible to pass to the considerat
sidereal system. The star-streams discove
and the form of the Galaxy suggest that it is
of many vast star clouds which move at lea
in the plane of the Milky Way. There is a
for the mutual interactions of the memb
cloud to reduce it to the spherical or sym
form. Moreover, the stars of smaller mass
greater velocities at the expense of the lar
in a mixture of gases of molecules of diff
lighter ones on the average move faster
ones. The fact that the individual sta
spherical would argue that they have not h
the symmetrical form of equilibrium, if it
fact that their passage through and ne
clouds may occasionally introduce great i

But all the star clouds which together co

parsecs and that the total numb… is, either the run-
Although the assumptions are … Galaxy entirely, or
the facts, it is believed that th… me more and more
order of magnitude. And und… m of its parts.
time required for a star to pa… stars at once arises.
to the opposite is approximat… ur Galaxy, perhaps
this is probably less than the a… ities have been de-
have traveled in geological tim… first alternative is
the boundaries of the stellar sy… r at first to be im-

Whatever may have been th… mous time required
star, these results, though they … m to another. But
numerically, imply that the st… ly leave our Galaxy,
able mixing. So far as can be … s might not equally
process will continue in the fu…
form the Milky Way will beco… , for if a large star
and the motions of the stars mo… velocity of the small
of smaller mass will acquire hig… of favorable close
ones, at rare intervals every st… gh velocities which
star, and possibly at intervals o… nalogous to the de-
Galaxy will encounter other gal… l cases in a mixture
and made irregular by them. … highest velocities.

280. Runaway Stars. — Sinc… s that the intervals
of a large group of stars is one hu… that the process de-
motions, the spectroscope furn… haps astronomers in
which the stars move. The ave… termine from their
near the sun is about 1.8 time… and the velocities
22 miles per second. This is 7.5 … gth of time during
or one parsec in about 27,000 y… been subject to

The stars, however, do not all … the most won-
mately the same velocity. The … globular star
are evidenced both by their pr… generally less than
radial velocities. The star havi… parent diameter of
motion,[1] namely, 8″.7 per year, … r to the unaided

[1] Professor Barnard has just (June, 1… shows that they
star in Ophiuchus whose annual prope… most splendid of
has not yet been measured.

and by astronomers is known as C. Z. 5 h. 243, or No. 243 in the fifth hour of right ascension in the Cordoba Zone Catalogue. It was discovered by Kapteyn in 1897 from the measurement of plates taken by Gill and Innes at the Cape Observatory, in South Africa. Its actual velocity is 170 miles per second, or nearly 8 times the average velocity of the stars. The star known as 1830 Groombridge has a proper motion of 7″ per year. Its parallax, which is not yet accurately known, can scarcely exceed 0″.1 and its velocity probably exceeds 200 miles per second. The star 61 Cygni is another one in Table XVI which moves at a high speed, though its velocity is exceeded by the velocities of quite a number of other known stars.

The stars having high velocities are called "runaway stars" because, unless they pass very near other stars in their journey through space, they will escape, like molecules from a planet, from the gravitative control of the stars which constitute the Galaxy, and will recede from them forever. This conclusion is inevitable unless the total mass of the sidereal system is much greater than has hitherto been supposed. Even if the extravagant assumption is made that there are 1,000,000,000 stars, each as massive as the sun, in a spherical space whose radius is 1000 parsecs, it is found that a star moving through its center with a speed exceeding 72 miles per second will entirely escape from the system unless, in its journey toward the surface, it passes near at least one other star in a particularly favorable way so that its velocity is much reduced. Since the probability of such a near approach is very small, we are forced to the conclusion that these stars with high velocities are only temporary members of our Galaxy. The only alternative is that the mass of the system is at least 10 times as great as has been estimated.

If the total mass of the stellar system is greatly in excess of the estimates which have been made, the resulting attractive forces are greater than the centrifugal forces due to the average motions of [illegible] refore, the stars must

There is no doubt that the paths of the stars eventually curve, but the time covered by our observations is as yet far too short for us to detect these deviations. It compares with the vast intervals required for the stars to move across the sidereal universe as one tenth of a second compares with the period of the earth's revolution around the sun.

The first question that springs to the mind is whether the stars travel in sensibly fixed and closed orbits similar to those of the planets, or move on indefinitely throughout the region occupied by the stars without ever retracing any parts of their paths. Since observations cannot at present answer this question, the reply must be based on dynamical considerations. There is clearly no central mass among the stars and there is no center about which they seem to be distributed with anything approaching symmetry. Moreover, their motions give no hint that they are moving, even temporarily, around some central mass or point.

The conclusion is inevitable that the stars describe more or less irregular paths, in the course of time probably extending into all parts of the sidereal system. In fact, the Galaxy was likened by Kelvin to a great gas in which the stars correspond to the molecules. When they are far apart their mutual attractions are inappreciable, just as molecules do not interfere with the motions of one another except at the times of collisions. If two stars should collide they would probably coalesce, the heat generated by their impact changing them into the nebulous state. This would be quite different from an elastic rebound of molecules. But actual collisions would be excessively rare and near approaches would be relatively much more frequent. A near approach is dynamically equivalent to an oblique impact of perfectly elastic bodies, as is illustrated in Fig. 170. In this figure C is the center of gravity around which as a focus the two masses (assumed equal) describe hyperbolas. It is easy to see that the motion before and after near approach is similar to that of two elastic spheres colliding a little to the right of

their respective centers. Consequently there are some good grounds for comparing the sidereal system to a vast mass of gas.

There are, however, fundamental differences between a gas and the stellar system. In a gas the collisions are the important events in the history of a molecule, and are the only appreciable factors which influence its motion. In the stellar system the near approaches of a given star to some other one are excessively rare, and the attraction of the whole system is the primary factor determining the motion of the individual star. Or, more particularly, a molecule in a vessel of ordinary gas has thousands of millions of collisions with other molecules per second, while the attraction of the whole mass has no appreciable effect on its motion. But in the sidereal system, a star will in general travel several times from one of its visible borders to the opposite one without once passing near enough to another star to have its motion radically altered by the latter, while its motion is controlled by the attraction of the whole mass of stars.

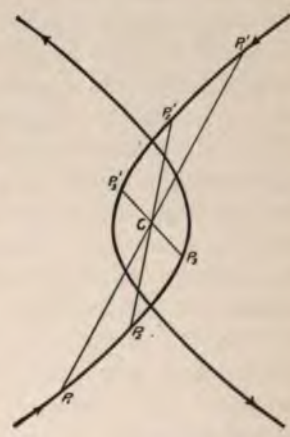


FIG. 170.—Near approach of two stars is similar to an oblique collision of elastic bodies.

It is difficult to realize the great distances which separate the stars and how feeble are the forces with which they attract one another. If the earth were at rest, it would fall toward the sun less than one eighth of an inch the first second. The distance of the relatively near star Sirius is 500,000 times as great; and in spite of the fact that its mass is 3.4 times that of the sun, in a whole year it would give the sun

be observable inside of

STIONS

$\angle E_1S'E_2$
$\angle SE_2S'$.

5 parsecs of the sun; what is
stars?
Herschel's observations, Art.
which he drew. If this conclu-
cepted?
red with an error not exceeding
be determined with this degree
275 in 100 years?
two stars are moving in parallel
ich they apparently move, as seen
whose direction from the earth is
move (Art. 277).
n is somewhat below the average of
hat are the probabilities of the rela-
the observed stars?
y is 1100 parsecs (end of Art. 279),
at its present speed to pass from the
its borders?
1830 Groombridge is 200 miles per
how long will be required for it to
ch our Galaxy will appear as a hazy

s, and if the distances between them
like the distances between the stars
the stars, how long will be required for
our Galaxy to another?

THE STARS

A few double stars have been known
ion of the telescope, but William
stronomer to search for them sys-
ure the distances and the directions
one another. His purpose in meas-
mine the parallax of the nearest ones

as the square of the distance from the cen
second, it varies directly as the distance fr
In a cluster whose radius is 5 parsecs and
50,000 stars, each having the mass of the su
quired for a star to move from the surface t
the first case is nearly 800,000 years, and i
1,100,000 years. The actual time is of the or
years. Since thousands of these excursions
sary to reduce a group of stars with conside
ties in distribution to the symmetrical form
age of these systems must be enormous. O
excursions from the periphery to the center
require 1,000,000,000 years. It is improb
number is too large (it may be many times
it follows that either the stars exist an enc
luminous bodies, or much of the dynamical
clusters was completed before the star st
there has been such a preceding stage. And i
from the symmetry of the clusters that for a
of millions of years they have not passed nea

No rapid motions of stars in the globular c
expected. With 50,000 stars, each equal to
distributed uniformly throughout a sphere
5 parsecs, the velocity of a permanent meml
at its center would be only about 4 miles pe
the actual clusters have strong central co
velocity for the ideal case would be consid
by stars near their centers. Suppose they n
per second at right angles to the line of sight.
of 1000 parsecs they would move with respe
of the cluster only one second of arc in 300 ye
if the assumptions as to the distance or m
the result will be wrong, and, besides, a certa
of the stars, especially those of smallest
motions in excess of the mean velocities. B
able that relative motions of the members



such a large number of stars so nearly in
the earth would have shown him that
imity could not be accidental. He re
in a few years, for his observations sh
siderable number of cases that the t
revolving around their center of gravi
of all stars consisting of single primary
by families of planets, there are many
of approximately equal mass and dime
know, they may or may not have plan
such small objects shining entirely by
be beyond the range of our telescope
thousand times more powerful than an

The names that stand out most prom
star astronomy of the nineteenth c
Struve, Dawes, John Herschel, and
ham's great catalogue of double stars
descriptions of about 13,000 of these ob
ones are constantly being discovered,
heavens have now been very thorou
powerful telescopes. At the Lick Obs
the whole heavens to at least −14° d
by Hussey and Aitken and completed

Period	Semi-axis
81.2	23.3
48.8	20.0
39.0	10.4
300.(?)	47.4
88.4	26.8
180.0	28.2
45.8	8.2
26.3	7.7
34.5	13.5
11.4	3.7
200.(?)	21.5

are given in years
distance from the sun
n's mass, and the lu
y at the same distan
interesting thing b
ses of all of these st
nd, with the excep
differ greatly from
ough pairs of stars i
eneral conclusion.
ach of the two com
their center of gra
n be computed. T
of two stars with
stem is very difficult
eighboring stars, or
d. In only a few c
The discussions of
hat probably in all
ive, a result which is
found in earlier inves

years, for Delta Aquilæ, to hundreds and p
of years. The planes of their orbits a
angles to the line joining them with the e
rule, we see their orbits in projection. In
42 Comæ Berenices is sensibly edgewise t
most interesting things about the orbits
they are generally considerably eccentric.
in See's list the average eccentricity was 0.
that of the planetary orbits. The orbit
Gamma Virginis has an eccentricity of 0.9
greatest distance of the two members of t
other is 19 times their least distance.

284. Masses of Binary Stars. — The
planets which have satellites are found fr
distances of their respective satellites
masses of Mercury and Venus are found
tions for other bodies, especially comets
celestial bodies are found only from their
bodies. It is evident, therefore, that the
remote from all other visible bodies can
when the dimensions of the orbit and th
tion of a binary pair are known, their con
computed just as the mass of a planet is

The periods of binary stars are det
observations of their apparent positions
of the orbit of a binary pair can be det
apparent distance apart and their distan
The chief difficulty lies in the problem of fi
for only a small number of stars are with
tance from the sun.

Those binary stars whose periods and
with sufficient approximation to make t
tions of value are given in Table XVIII.
those whose parallaxes are less than 0″.2
uncertainty, and the probable error is gr
are less than 0″.1.

285. Spectroscopic Binary Stars. — The sp contributed very important results to the s stars. Its application depends upon the fact the observer to determine whether a source proaching or receding (Art. 226). Suppose motion of a binary system passes through t represented in Fig. 172. When the stars are i *A* and *B*, one is receding from, and the other toward, the earth. If they have similar spe trum of the combined pair will consist of dou

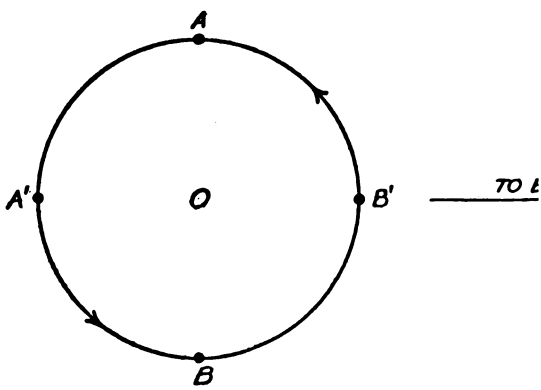
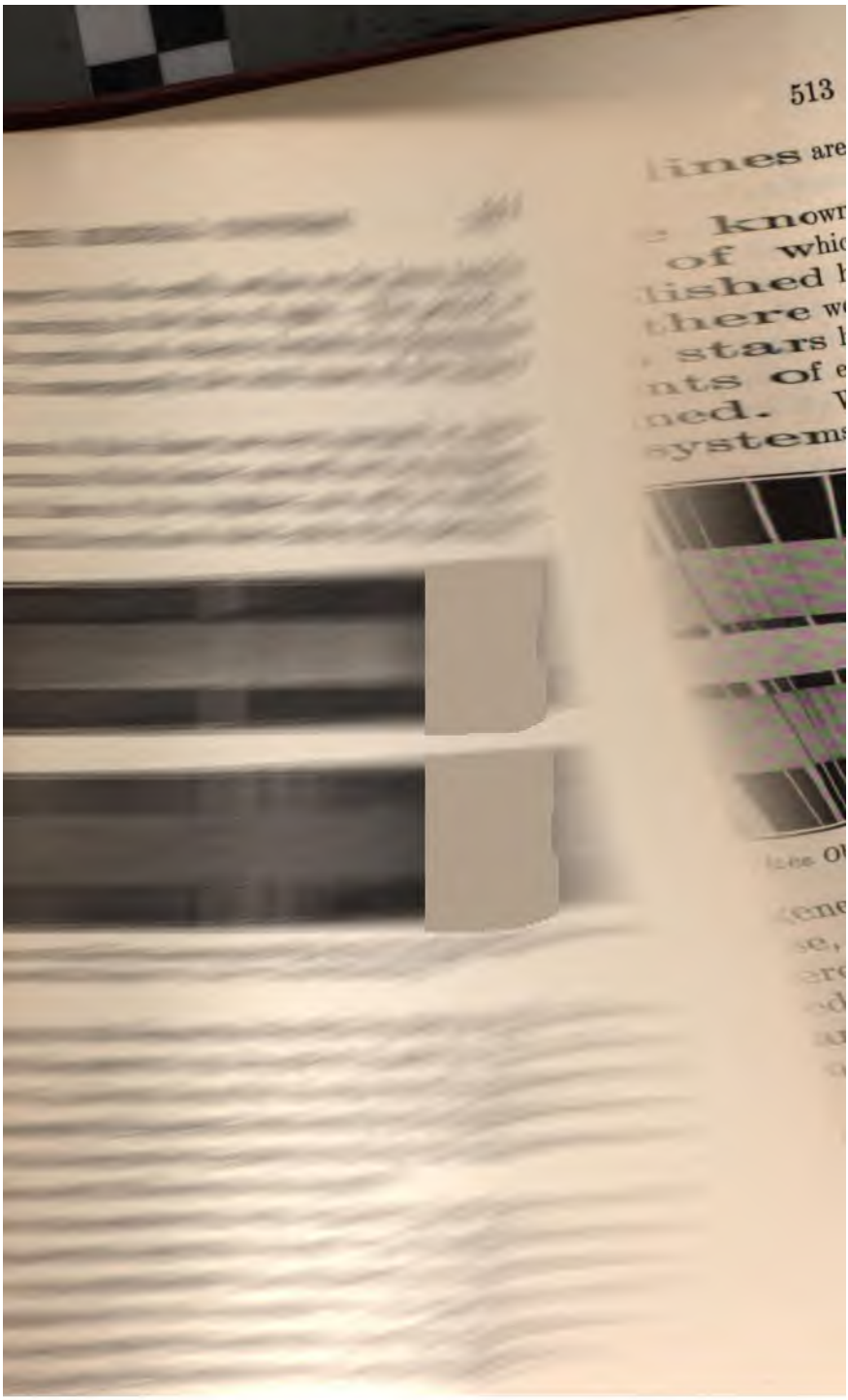


FIG. 172. — Orbit of a spectroscopic binary

173), for the lines from one will be shifted t while the lines from the other will be displac violet. When the stars have made a quarter around their center of gravity *O* and have and *B'*, the lines will not be displaced becaus neither approaching toward nor receding fron After another quarter of a revolution they again because *A* will be approaching and *B* r

The data furnished in this way by the sp very important because, in the first place, th the lines determines the relative velocity of th orbits. This is true whether the system as



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those of the sun, it seems probable that the orbit of the pair is so inclined that the computed masses are much too small.

Polaris. The pole star has two darker companions discovered spectroscopically by Campbell in 1889. One is very close to the bright star and revolves around it in a period of a little less than 4 days, while the second companion is much more distant and requires about 12 years to complete a revolution. These stars are all quite distinct from the faint telescopic companion to Polaris.

Alpha Centauri. Alpha Centauri is at the same time a visual and a spectroscopic binary. Moreover, its parallax has been very accurately determined by direct means, so that the actual distance of the components from each other and their masses can be determined (Table XVIII). Since the same results can be determined spectroscopically, their comparison affords a valuable check on the accuracy of the results. The spectroscopic data were obtained by Wright at the branch of the Lick Observatory in South America, and the results obtained from them agree almost exactly with those based on other methods. But the spectroscope gives the additional fact, which cannot be determined otherwise, that Alpha Centauri is approaching the sun at the rate of 13.8 miles per second.

287. Variable Stars. — A star whose brightness changes is said to be a variable. The first known variable, Omicron Ceti, was discovered by Fabricius in 1596. The variability of Algol was definitely announced by Goodricke in 1783, though it seems to have been noticed a century earlier. The following year he recorded the variability of Beta Lyræ. But variable stars were not discovered in any considerable numbers until toward the close of the nineteenth century. Now more than 3000 of these objects are known in addition to those which have been found in considerable numbers in some of the globular star clusters. Some of them vary regularly and periodically, with periods ranging from less than a day to more than two years; others vary irregularly with-

In 1908 Frost announced that Alcor is a spectrosc
of short period in which both spectra are observab
fore Mizar is a visual double each of whose compo
spectroscopic binary, and the neighboring Alco
binary.

Spica. One of the earliest known spectrosco
is the first-magnitude star Spica whose spectra
found to vary by Vogel in 1890. The spectr
fainter component has also been observed. Th
the pair is 4 days, their mean distance from ea
about 11,000,000 miles, and their masses (neglect
sible reduction due to the inclination of their
respectively 9.6 and 5.8 times that of the sun.
is receding from the sun at about 1.2 miles per se

Capella. The first-magnitude star Capella i
scopic binary, the spectra of both stars being visib
the period is 104 days and the mean distance (po
reduced by the inclination of the plane of the o
50,000,000 miles. With these data the masses o
are found to be at least 1.2 and 0.9 that of the s
orbit has a very small eccentricity. These sta
ceding from the solar system at the rate of near
per second. The parallax of Capella has been in
with the utmost care by Elkin, who found for it

g the hori-
portional to
arts marked
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e the bright-
If the fainter
ntirely dark,
minimum.
component is
is essentially
00 stars of this
Algol variables.
of their periods,
nly 12 of which
ity of their light
ir short periods
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ectroscopic binary
h the methods and
ta obtained in the
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tensive. The spec-
efore the dimensions
both stars are lumi-
es the dimensions of
sses are known, their
has been found by
rs that the mean den-
re are sufficient obser-
of the sun. This is a
that usually one of the
current doctrine, in a
on. It should be added

out any apparent rule or order. Some fla
for a short time and then sink back mor
manent oblivion. It is certain that the b
star varies slowly because of its changing
sun, if for no other reason, but there i
evidence of a change for this reason.

Variable stars are classified according
of their light changes, and the principal ty
in the following articles. It must be rem
that variable stars are strange objects
merous exceptions to all rules.

288. Eclipsing Variables. — If the pla
binary pair passes very nearly through

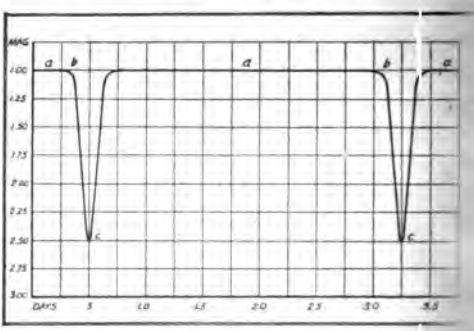


FIG. 175. — Light curve of typical eclipsing vari
star.

except when the brighter star is ecli
begins to eclipse the brighter one, tho
rapidly until the time of greatest ob scu
a rule the star rapidly regains its n orm
ever, in some cases the dark star i v
eclipse persists for a considerable ti me
remains at minimum for a few i ins
hours.

The variability in the brightne is that they
by a curve. In Fig. 175 the cu its compared

it is a spectroscopic binary. He found that
mass of the system is two thirds that of the s
star has twice the mass of the darker one, th
tween their centers is about 3,000,000 miles,
of the stars are about 1,000,000 and 800,000 n
density is about one fourth that of the sun
found that for the similar system Delta Libra
also one fourth that of the sun.

There are several variations from the
variable. In one the stars are of unequal
bright. Then each eclipses the other, but t
is different in the two eclipses, and the ligh
minima of different depths. There are oft
which have not yet been explained. Somet
increase slightly for a number of years an
again, showing possibly the presence of a thi
times the minima as determined photogr
occur at the times found by visual observat

289. Variable Stars of the Beta Lyræ stars of the Beta Lyræ type are closely
which have been considered; in fact, the di
the two classes seems to be disappearing.
continuously from maximum to minimum

cally with the periods of their light variations. The
conclusion has been that they are spectroscopic bina
that the changes in light are abnormal eclipse phen
While the light changes and spectral shifts agree in
they absolutely disagree in phase. That is, int
the spectroscopic data in the ordinary way, these
brightest when the principal stars are approach
observer and faintest when they are receding, in
having their minima when they are eclipsed. E
there are inconsistencies in the interpretations,
questionable whether eclipses have anything whate
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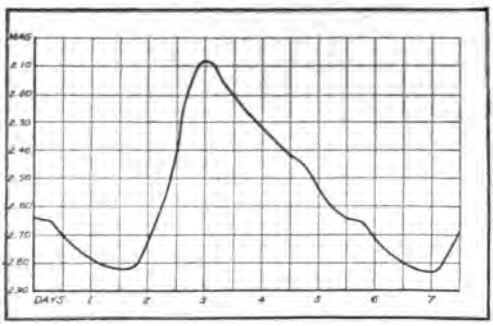


FIG. 177. — Light curve of a variable star of the Delta Cephei type.

haps by collisions with masses of planetary dimen
has been found that very moderate oscillations would
for the variations in the rates of radiation. Acco
this hypothesis, the shifts of the spectral lines are p
partly by internal motions of the stars and partly
effects of alterations in pressure of the radiating pa

291. Variable Stars of Long Period. — A maj
variable stars belong to the class whose periods ran
50 to several hundred days. They are not periodi
strict use of the term which is applicable to the Algol v
yet their light varies in an approximately periodic
But the intervals between maxima, or between mini

hough not
ir changes,
uted widely
00 of these
ied, astrono-
uliarities.
have been
nostly in the
en, and then
few weeks or
n rise to one
standing later
e of the most
re any records
time as bright
he attention of
The interest of
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rn it was as bril-
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uch splendor.
stars discovered
ore observers are
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aphy. In the last
discovered, 15 of
ie record of the sky
ollege Observatory.
from 1572 to 1886,
s first systematically

or new stars. A de-
od idea of the charac-
st interesting and best
e discovered by Ander-
On the 23d of February

the remarkable fluctuations which are ... examination of the stars of this class.

292. Irregular Variable Stars. — In ... not brighter than of variable stars so far enumerated, ... of four days in variations have no semblance of ... than 20,000 fold. out with relatively great brilliancy ... of its light, and counted in years. These stars are ... magnitude, or near red. Others unaccountably fade away ... considerable power sometimes become invisible through ... after its maximum though they had been ordinarily visible ... is shown in Fig. 179. These stars are sometimes associated ... with faint nebulous masses.

293. Cluster Variables. — A very ... portant discovery was made in the ... teenth century by Bailey at the Sou ... the Harvard Observatory. He fou ... globular cluster, Omega Centauri, ... out of the 3000 which he examined. ... omers have found similar variables ... star clusters. In a given cluster the ... nearly the same, usually a magnitud ... of the light variation is essentially ... are approximately the same, gene ... Their light curves are closely simila ... of the Delta Cephei type, and it is ... the cluster variables should be co ... The brightness increases with g ... minimum to a luminosity at maxim ... as great. Then they diminish i ... slowly to their minimum, at wh ... stationary for a few hours at mo ...

The approximately equal perio ... of the cluster variables indicate ... alike in spite of the enormous dist ... Possibly they were once much mo ... some extent because of slightly o ...

The changes in the spectra of the novæ are as remarkable as their changes in luminosity. Very early in their development they have (at least in case of those ... spectra. Shortly ... case of Nova Aurigæ, ... y star whose spec- ... ark lines and bright ... displacement of the ... the Doppler-Fizeau ... of over 200 miles per ... the same basis, an ... 00 miles per second. ... the correctness of ... planation is at hand. ... in general. As ... and the bright lines ... that in the novæ they ... whole.

it was brighter than Capella, while an examination
photographs of the region taken by Pickering and by S
Williams showed that on the 19th it was not brighte
the 12th magnitude. In the short space of four da
rate of radiation had increased more than 20,000
Twenty-four hours later it lost one third of its ligh
within a year it had dwindled to the 12th magnitude,
the limits of visibility with a telescope of considerable
Its light curve for the first three months after its ma
is shown
179.

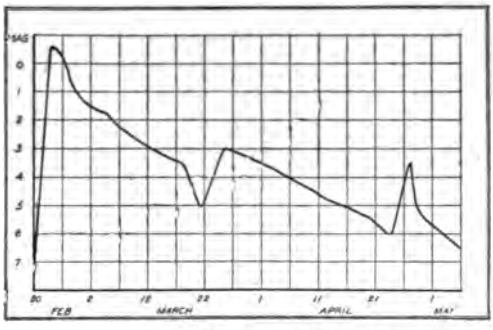


FIG. 179. — Light curve of Nova Persei.

The cha
the spectr
novæ are
markable
changes i
nosity.
early in t
velopment
have (at
case of
stars which were observed early) dark-line spectra.
thereafter bright lines appear. In the case of Nova
discovered in 1892, and the first temporary star who
trum was examined in any detail, the dark lines an
lines were both visible at one time. The displacemen
bright lines showed, on the basis of the Doppler-
principle, a velocity away from the earth of over 200
second, while the dark lines showed, on the same b
approach toward the earth of more than 300 miles per
There are abundant grounds for doubting the correc
this interpretation, but no satisfactory explanation is
These phenomena are characteristic of novæ in gener
they become fainter the dark lines vanish and the brig
characteristic of nebulæ appear, except that in the no
are broad while they are narrow in the nebulæ.

Type I, in Secchi's system, includes Types B and A of the Harvard system. Type B is often called the Orion type because of the abundance of these stars in Orion, or the helium type, because the absorption lines are due almost entirely to helium, while the metallic lines which are characteristic of the sun's spectrum are absent. The Type A, or Sirian stars, are characterized by strong hydrogen absorption lines in their spectra, and almost complete absence of metallic lines.

Type II. The stars of the second type are somewhat yellowish; they are called solar stars because their spectra are

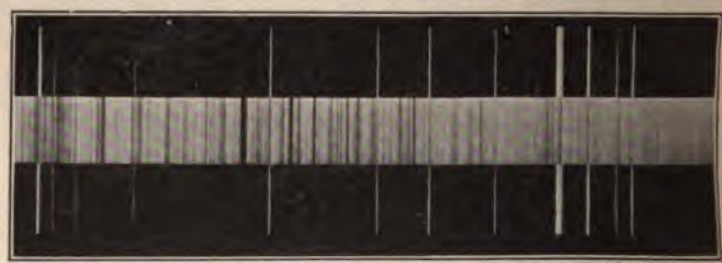


FIG. 182. — Spectrum of Beta Geminorum (Harvard Class K). *Photographed at the Yerkes Observatory.*

similar to that of the sun. That is, the lines of helium are absent, the lines of hydrogen are still present, and there are many fine metallic lines. The stars of the second type are about as numerous as those of the first type.

Secchi's second type includes three classes of the Harvard system. Those nearest like the Sirian stars are called Type F, or the calcium type. In their spectra the hydrogen lines are still conspicuous, though somewhat reduced in density, and two lines, known as H and K, due to calcium have become conspicuous. Following the class F is the class G, of which the sun is a typical member. Then come the stars of Type K, of which Beta Geminorum and Arcturus are examples, in which the intensity of the hydrogen lines is reduced until they are less conspicuous than some of the

metallic lines. The spectra of these stars are given in Figs. 182 and 183.

Type III. Stars of the third type are red, and the two most conspicuous examples of them are Antares and Betelgeuze. Only about 500 of these stars are known, and many of them are variable. Their spectra show heavy absorption bands, due almost entirely to titanium oxide, which are sharp on their borders toward the violet and which gradually fade away toward the red. The fact that a compound exists in these stars indicates that their temperatures are lower than those of Types I and II. The same thing is indicated by their colors in accordance with the first law of spectrum analysis (Art. 223). In all known cases they have very small proper motions, which means that they are immensely re-



FIG. 183. — Spectrum of Arcturus (Harvard Class K). *Photographed at the Yerkes Observatory.*

mote from the sun. Hence such brilliant stars as Antares and Betelgeuze, whose light is largely absorbed, must be enormous objects. They are almost certainly many thousand times greater in volume than our own sun.

The stars of Secchi's third type are of Type M in the Harvard system. They are divided into two chief subclasses, Ma and Mb; a third subclass Md includes the long-period variable stars whose spectra show bright hydrogen lines in addition to the bands characteristic of the whole type.

Type IV. The 250 stars of Secchi's fourth type are all faint and of a deep red color. Their spectra have heavy absorption bands, or flutings, sharp on the red side and indefinite on the violet, being in this respect opposite to the stars of the third type. The absorption bands in this case are probably due to carbon compounds. These stars are all

very remote from the sun, and nothing is known of their absolute magnitudes, or of their masses and dimensions.

The Wolf-Rayet Stars. There is another class of stars, discovered in 1867 by Wolf and Rayet at the Paris Observatory. They are Type O, having five subdivisions, in the Harvard system. Their spectra consist of fairly continuous backgrounds on which are superimposed many dark lines and bands, some few of which are due to helium and hydrogen, but most of them to unknown substances. They contain in addition many bright lines. The metallic lines of the solar spectrum are quite unknown in these stars. Of the more than 100 stars of this type so far discovered, all are situated either in the Milky Way or in the Magellanic Clouds in the southern heavens, which have most of the characteristics of the Milky Way.

296. Phenomena Associated with Spectral Types. — A large number of phenomena combine to show that the classification of stars according to their spectra is on a fundamental basis. The order of arrangement from the simplest to the most complex spectra is:

Secchi's Types:	Wolf-Rayet;	I;	II;	III;	IV.
Harvard Types:	O;	B, A;	F, G, K;	M;	N.

If the gaseous nebulæ were included, they would be put ahead of the Wolf-Rayet stars. There is a fairly continuous sequence of spectra from Type O to Type M, but there is an abrupt break between Types M and N.

The principal phenomena which are associated with the spectral types and which agree on the whole, in arranging the stars in the same order, are:

(*a*) The average radial velocities of the stars, determined largely at the Lick Observatory and its southern branch, and discussed by Campbell, are slowest for stars of Type B and increase to Type M. The results, as given by Campbell, with velocities expressed in miles per second, are:

Types:	B,	A,	F,	G,	K,	M,	Planetary Nebulæ.
Velocities:	4.0,	6.8,	8.9.	9.3,	10.4,	10.6,	15.7

(*b*) The average velocities of the stars across the line of sight, as determined by Lewis Boss, show a similar relation to the spectral type. The results are:

Types:	B,	A,	F,	G,	K,	M.
Velocities:	3.9,	6.3,	10.0,	11.5,	9.4,	10.6.

These results together with those depending on the spectroscope establish the fact that the stars of Types B and A move on the average only about half as fast as those of Types G, K, and M.

(*c*) In Kapteyn's star-stream I, the B and A stars are relatively numerous, the F, G, and K stars occur less frequently, and the red stars are very few in number. In the star-stream II, the B and A stars are not numerous, the F, G, and K stars occur in relatively great numbers, and the M stars are scarce.

(*d*) While there are two great star-streams, there are very many divergencies from them on the part of individual stars. The stars of Type B scarcely show the star-streaming tendency, those of Type A conform very closely to the two streams, and succeeding types show more and more of heterogeneity of motion.

(*e*) On considering only stars brighter than magnitude 6.5 so as not to have the results influenced by the myriads of remote stars, it is found that the B stars are 10 times as numerous in the Milky Way as near its poles, the A stars are less strongly condensed in the Milky Way, and finally, after continuous gradation through the various types, the M stars are scattered uniformly over the sky.

(*f*) For a given magnitude the stars of Type B are more remote than those of Type A, which, in turn, are more remote than those succeeding down to Type G; then, beyond Type G, the distances increase to stars of Type M, whose distances are exceeded only by the B stars. This means, of course, that the B stars are most luminous, the A stars less luminous, the G stars least luminous, while the M stars are more luminous than any except the B stars.

(*g*) The proportion of B stars which are spectroscopic binaries is large, the proportion is less for the A stars and it decreases through the list of types to M.

(*h*) Lower limits to the combined masses of spectroscopic binaries can be determined (Art. 285). The average mass of those of Type B is about 7.5 times the average mass of all other types.

(*i*) The average period of spectroscopic binaries of Type B is very short, the average is a little longer for stars of Type A, and increases through Types F, G, K, and M.

(*j*) The average eccentricity of the orbits of spectroscopic binaries is small for stars of Type B, is larger for stars of Type A, and is increasingly larger for stars of the Types F, G, and K, in order.

297. Evolution of the Stars. — All the resources of science have been taxed to the utmost in attempting to discover the present constitution and properties of the sidereal system. At the best, astronomers have barely begun to explore the wonders of that part of infinite space which is within the reach of modern instruments. Moreover, their observational experience is limited to a moment of time compared with the immense ages required for appreciable changes to take place in the heavenly bodies. Hence it may seem presumptuous for them to attempt to discover the mode, or modes, of evolution of the stars. Any theories of stellar evolution that may be developed at the present time are probably no more than first approximations, and they may be entirely wrong.

Astronomers almost universally hold that the stars have contracted from the nebulæ, and most of them believe that with increasing age they have gone, or are now going, successively and in order through the spectral types B, A, F, G, K, and M. The B stars are of very high temperature and are pouring out radiant energy at an extravagant rate. After they cool somewhat it is supposed that they become [illegible]e A. Their spectra are supposed to be simple

because all compounds, and possibly some elements, are broken up and dissociated at those high temperatures. With further loss of heat they are supposed to pass successively through the other spectral types until, at the M stage, compounds exist in their atmospheres. Beyond the M stage their light diminishes and they finally become, in the course of time, cold and dark, and they remain in this condition until, perhaps, they are again reduced to the nebulous state by collision with other stars. All the forms in the chain from nebulæ to relatively dark stars are known to exist from observational evidence. The many other characteristics which arrange the stars in nearly, or exactly, the same order are regarded as strongly supporting the theory.

The theory of the evolution of the stars has strong resemblances to the Laplacian theory of the development of the solar system. This is only natural in view of the general acceptance of the theory of Laplace almost up to the present time. As additional facts have been discovered they have been placed in this scheme, often without inquiring if they would not fit as well in some other theory.

Laplace started with an intensely heated and widely expanded solar nebula and he supposed that it has cooled down to its present temperature. Helmholtz supplemented and corrected this theory by proving that contraction would develop an enormous amount of heat and greatly retard the process of cooling. The conclusions of Helmholtz have been given place in the theory of the evolution of the stars. Lane made a further very important supplement to the work of Laplace when he proved that if a body in a monatomic gaseous state contracts, heat is produced in quantities not only sufficient to make up for that which had been radiated away, but also sufficient actually to increase its temperature. In spite of the fact that the results of Lane have been current for almost fifty years, they have often been ignored in their application to the evolution of the stars. If the stars of any type are in a tenuous monatomic gaseous condition and

contract, their temperature will inevitably rise and continue to rise until they cease to be entirely gaseous and monatomic.

Consequently, if the stars of the types B, A, F, G, K, M are in the order of decreasing temperature and are gaseous, the logical conclusion on the basis of the supplements to Laplace's theory is that the evolution proceeded in the reverse order. Of course, the stars may not all be completely gaseous. This has given rise to the theory, proposed by Lockyer and amplified and ably supported by Russell, that the nebulæ contract into tenuous red stars of Type M which have low temperatures; with loss of heat they contract, their temperatures rise, their spectra become simpler until they reach their climax in Types A and B; after this they cease to be completely gaseous, and with increasing condensation and liquefaction, their temperatures decline and their spectra proceed back through the types F, G, and K to M. The cogency of the arguments on which these conclusions rest cannot be denied, and many observational data are quite in harmony with them. But there are also some things (for example, the high velocities of the nebulæ, Art. 301) which have been thought to be strongly opposed to them. The two theories are alike in starting from nebulæ and ending with cold and lifeless suns.

298. The Tacit Assumptions of the Theories of Stellar Evolution. In every theory there are many more or less tacit assumptions, some of which may be of great importance. It has been found by a large amount of experience that errors more frequently enter through unexpressed hypotheses than in any other way. This has been particularly true in mathematics where it is relatively easy to determine precisely the location of the error that has been made in any course of reasoning. It follows that one of the best ways of avoiding errors is to express fully all the hypotheses on which reasoning is based. And quite aside from this, it is useful and important to know all the bases on which conclusions actually rest. Consequently, the tacit and imper-

fectly established assumptions on which the present theories of stellar evolution are founded will be enumerated; it will be found that at the present time most of them must remain simply assumptions.

(*a*) *It is assumed that the evolution of the stars is from nebulæ to dense bodies and not in the opposite direction.*

The best evidence in support of or against a proposition is usually observational; when observational evidence is lacking, we must resort to reasoning based as far as possible on principles which have been established by experience.

There is as yet no observational evidence that nebulæ or stars contract; observations have extended over so short a time that it could not be expected. On the other hand, in the case of the novæ, stars are observed to acquire the characteristics of the Wolf-Rayet stars, which border on the planetary nebulæ. Of course, this may be quite exceptional, but it should not be neglected. Consequently, in this matter there is no conclusive observational evidence.

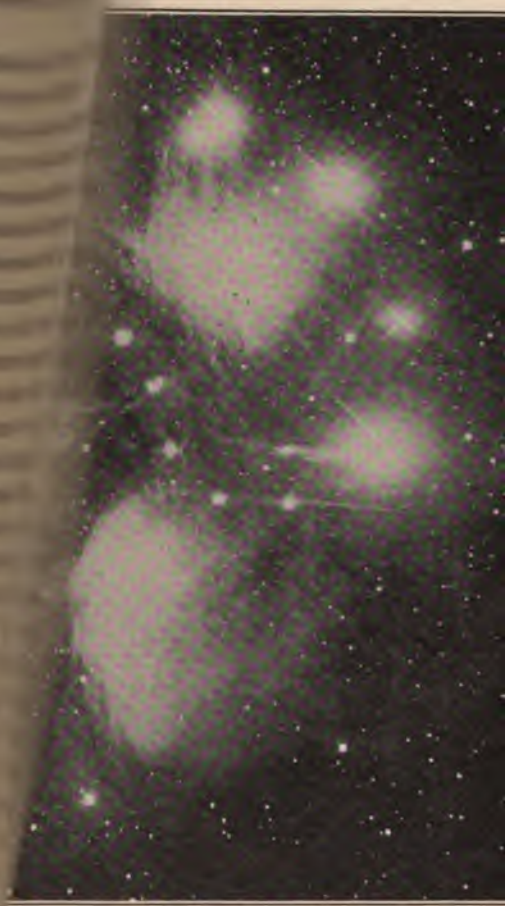
The principal known force which tends to produce condensation is gravitation. In the case of the stars this force is balanced by the expansive forces due to their high temperatures. If their heat is produced only by their contraction, as they lose heat by radiation, they certainly contract. But the contraction theory is inadequate to explain the heat which the sun has radiated (Art. 219), and it seems very probable, if not altogether certain, that stars have other important sources of energy. As has been suggested, the heat of the sun is probably due in part to the disintegration of radioactive substances. Perhaps in the extreme conditions of pressure and temperature prevailing in the deep interiors of stars the process of disintegration is greatly accelerated and is going on in all elements. And probably there are very important sources of energy not now suspected, just as the sub-atomic energies were not suspected a few years ago.

Now suppose the amount of energy generated in a star

contract, their temperature will inevitably ri
to rise until they cease to be entirely gaseous

Consequently, if the stars of the types B,
are in the order of decreasing temperature
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cease to be completely gaseous, and with i
sation and liquefaction, their temperatures
spectra proceed back through the types F
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298. **The Tacit Assumptions of the Evolution.** — In every theory there are
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leiades. These stars are surrounded by nebulous mas
ume. *Photographed by Ritchey with the two-foot refle*
ervatory.

It is obvious that we do not know with any high degree of certainty in which direction stellar evolution is proceeding. Sound scientific method calls for keeping both of them in mind until a decision is reached on the basis of unequivocal evidence. Whichever of the two conclusions may prevail, the result will be unsatisfactory, for it will indicate a universe evolving always in one direction, leaving the origin unexplained. Possibly there are changes in both directions, and it may be that stellar evolution in some way and on a stupendous scale is approximately cyclical like most of the changes which come entirely within the range of our experience.

(*b*) *It is assumed that all stars have approximately the same chemical constitution; or, if not, that their spectra do not depend to an important extent upon their chemical constitutions.* One or the other of these assumptions is made tacitly when it is supposed that all stars pass in one direction or the other through several identical spectral types.

The spectroscope proves that the stars contain familiar elements; it does not prove that they do not contain some unknown elements, or that the known elements occur in all stars in the same proportions. The great diversities on the earth make it natural to conclude that there are important differences in the millions of stars in the heavens. Moreover, the different dimensions, densities, and absorption spectra of the planets lead to the same conclusion. The hypothesis that the stars are of approximately identical constitution must be considered improbable until it is supported by observational evidence.

It is too bold to assume that if the stars are differently constituted they nevertheless have the same spectra at the same temperatures. But the assumption actually made is not quite so bad as it at first seems, for the stellar spectra from B to F, and even G, are classified primarily on the basis of their hydrogen emission and absorption lines. Within these classes there is unity for great variety,

and indeed variety is not wanting. There is nothing obviously unsound in supposing that the character of the hydrogen spectra of the stars depends upon their temperatures. But the question is whether a star which has only helium and hydrogen lines can ever show the strong metallic absorption lines which are characteristic of stars of Types F and G. Fortunately, there is now direct evidence on this point, for there are certain variable stars which, at their maxima, are of spectral Types B or A, while, at their minima, they are of Types F or G. There is nothing inherently improbable in ascribing these changes in luminosity and spectra to

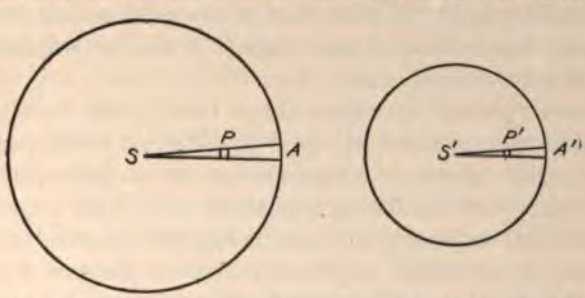


FIG. 185. — For a given density, the more massive the star the higher its temperature.

changes in temperature, produced, perhaps, by contracting and expanding oscillations of these stars.

(*c*) *It is assumed that, aside from the rate of change, the evolution of a star does not depend on its mass.* In considering this point the assumption that the spectrum of a star depends upon the temperature of its radiating surface, or radiating layer, should constantly be borne in mind.

It should be recalled in the first place that the known masses of the stars differ considerably (Art. 284), and it is improbable that the few which are known cover anywhere nearly the whole range. Consider two stars, S and S', Fig. 185, of the same material and equal density but one having twice the mass of the other, and fasten attention on unit

are in the ratio of only 8 to 1, differ in luminosity in the ratio of 1024 to 1. If a star were eight times more massive than the sun, it would have a spectrum of Type B or A, if these spectra indicate high temperatures, and it would be a star comparable to the most brilliant ones found in the heavens. On the other hand, if it were one eighth as massive as the sun, it would have a spectrum characteristic of low temperatures (Type M?), and would be a feebly luminous body.

Of course, it is not necessary that other stars should have the same density as the sun. It is known from eclipsing variables that comparatively few are as dense as the sun, and that the densities may be as small as one hundredth or even one thousandth of that of the sun. It can be shown that the temperature of a gaseous star is proportional to the cube root of the product of the square of the mass and the density. Hence, in order that a star having a density one hundredth that of the sun should be as hot as the sun, its mass must be about 10 times greater. But under these conditions its surface and luminosity would both be about 100 times as great as those of the sun. That is, a star nearly as brilliant as one of the Pleiades might be only one hundredth as dense as the sun if its mass were only 10 times greater. A star 10 times as great in mass and one tenth as dense as the sun would be 460 times as luminous.

It can be seen from this incomplete discussion that in order that a star shall have high temperature and great luminosity it must have a mass at least as great as that of the sun; for it is not probable that a much denser body would be in a gaseous condition. But the luminosity of a gaseous star is so sensitive a function of its mass that one 10 times more massive than the sun would be a brilliant object unless its density were exceedingly low; and one only one tenth as massive as the sun would be relatively faint, even if it were as dense as the sun. Therefore, it is not strange that no stars with very small masses have been found; one as small as one of the planets could not be self-

luminous while in a gaseous state. On the other hand, no star many times more massive than the sun has been found. Perhaps the reason is that the data respecting masses is yet so meager; perhaps the temperatures in massive stars become so great that their atoms disintegrate and the remains fly away into space.

(*d*) *It is assumed that the contraction of nebulæ into stars began at such a time, or at such times, and that the individual nebulæ had such masses that there has resulted the present sidereal system of nebulæ and stars in all stages from hottest to coldest.* The implications of this assumption are not at once fully evident; they can be brought out only by a mathematical discussion whose results alone can be given here.

On the basis of Stefan's law of radiation and the assumption that the heat of a star is developed entirely by contraction, it is found that the change of radius is directly proportional to the product of the time and the square of the mass. If there are other important sources of heat, and if the radiation is from a layer of varying depth instead of from the surface, the law may be much in error. But on the assumption that this result applies to the sun, it is possible to compute the time required for it to have contracted from any given dimensions. According to the contraction theory its radius is now diminishing at the rate of a mile in 44 years. Consequently, on this basis it has contracted from the orbit of Mercury in 1,500,000,000 years. At first thought this would seem to give a long supply of heat to the earth to meet geological needs; but if the sun ever filled a sphere as large as the orbit of Mercury and radiated according to Stefan's law, whatever the source of heat may have been, its temperature must have been so low that its rate of radiation could have been only a little more than one seven-thousandth that at present, a quantity altogether inadequate to support life on the earth. According to this contraction theory, 4,400,000 years ago the radius of the sun was 100,000 miles greater than at present, and its rate of

radiation was only two thirds that which is now observed. With this rate of radiation the theoretical mean temperature of the earth, determined by the method used for Mars in Art. 172, comes out 51° lower than at present (60° F.), or 23° below freezing.

The second part of the law gives the interesting and unforeseen result that the more massive a star, the more rapidly it contracts. Or, if the results are translated over into a relation between density and time, it is found that if a star of large mass and one of smaller mass start with the same density, the density of the large star will increase faster than that of the smaller one. The rate of change of density is proportional to the cube root of the fifth power of the mass. Therefore, if one star has 8 times the mass of another and they start contracting from the same density, it will arrive at some greater density in $\frac{1}{32}$ of the time required by the smaller star to reach the same density. As applied to the stellar system, this means that if the stars all started condensing from nebulæ at the same time, those which have the largest masses are at present by far the densest and hottest. The large stars are probably much hotter on the average than the small ones, but it is doubtful if they are denser. It must be remembered that these results depend upon the very questionable assumption that the heat of stars is due entirely to their contraction.

299. The Origin and Evolution of Binary Stars. — The great number of binary stars calls for a consideration of their origin and evolution. If the stars have condensed from nebulæ, it is natural to suppose that binary stars have developed from nebulæ which divided into two parts, or that the divisions have taken place after the condensing masses have reached the star stage. It is also conceivable that stars which originated separately have later united to form physical systems. Both of these theories will be considered.

Consider first the theory that the binary stars have orig-

inated by the fission of nebulæ or larger stars. The basis for the theory is the very reasonable assumption that the original nebulæ had more or less rotation, possibly quite irregular in character. In those cases where the amount of rotation, that is, the moment of momentum, was small, it is believed that single stars rotating slowly have resulted. In those cases where the moment of momentum was large, it is supposed that there has been separation into two parts.

There is some theoretical basis for this conclusion, though from a practical point of view it has generally been greatly overestimated. In a brilliant piece of work on figures of equilibrium of homogeneous fluids rotating as solids, Poincaré, following Maclaurin and Jacobi, showed that for slow rotation an oblate spheroid is a figure of equilibrium, for faster rotation an elongated ellipsoid is the corresponding figure, and for still faster rotations the ellipsoid has a constriction, suggesting that for still faster rotations the figure would be two very unequal masses. Now, when a nebula or a star contracts it rotates more rapidly because the moment of momentum is constant. Hence it seems reasonable to suppose that nebulæ and stars follow at least roughly the figures found by Poincaré for the homogeneous case.

There is one very important point of difference in the problem treated by Poincaré and that presented by contracting bodies. Poincaré considered masses all of the *same density*, but having different rates of rotation. In a contracting nebula or star both the density and the rate of rotation change. The increase in density tends to sphericity; the increase in rate of rotation tends to oblateness. The two effects almost balance each other, but the effect of increasing rotation prevails by a narrow margin. For example, if the sun contracts with loss of heat, it will not become so oblate as Saturn is now until its density is hundreds of times greater than that of platinum. This does not mean that a body contracting from a nebula may not divide into two parts at any stage of its development, but it shows that the

tendency for fission is very much smaller than has been supposed.

Suppose a star divides into two parts. Originally the two components will be rotating so as to keep their same faces toward each other. But with further contraction they will rotate more rapidly while their period of revolution remains unchanged. Then tidal evolution begins, and under these conditions Darwin has shown that the tides will increase the periods of rotation rapidly and the period of revolution more slowly. Moreover, if the original orbit had any eccentricity it will be increased. Consequently, as the age of a binary star having originated by fission increases, its period of revolution increases and the eccentricity of its orbit increases.

From an extensive study of the orbits of spectroscopic and visual binaries, Campbell has found that stars of Types B and A have short periods and nearly circular orbits, and that both the periods and the eccentricities increase, on the average, through the spectral types F, G, K, and M. One would be tempted to infer, in accordance with the theory of the evolution of stars through the spectral types from B to M, that binaries of Type B had recently originated by fission and that with increasing age they would go through the various spectral types with periods increasing correspondingly from a few hours to an average of more than a century, and the eccentricity from near zero to an average of about 0.5.

But such an inference would be entirely unwarranted and erroneous, for an ample consideration of the dynamics involved shows that when a nebula or star divides into two equal masses, tidal friction in any time however long is not competent to make the period more than about twice its original value; if the masses are unequal but comparable, as in the case of all known binaries, the period may be lengthened several fold. But it is altogether impossible for tidal friction to increase the period of a binary star whose

[redacted]

mass equal to the sun. At a great distance from each other their relative velocities might be anything from zero to several

hundred miles per second; take the most favorable case where it is zero. Suppose that at their nearest approach their distance from each other is as great as that from the earth to the sun. Under the hypotheses adopted they will have a relative velocity of about 37 miles per second. Suppose they encounter enough resistance from outlying nebulous or planetesimal matter, or from collision with a planet, to reduce their most remote point of recession after collision to 100 astronomical units. It can be shown that their velocity must have been reduced by $\frac{1}{200}$ of its amount, or by 0.185 mile per second. This would generate as much heat as the sun radiates in about 8 years. Consequently the expansive effect of the heat generated by the collision will not be important, and after the encounter the stars will be moving in an orbit whose eccentricity is 0.98 and whose period is about 250 years. The resistance could have been produced by collision with a planet whose mass was $\frac{1}{200}$ that of one of the suns. It follows that if a star passing the sun should meet Jupiter, something comparable to what has been given in the example wou'd result. Figure 186 shows the original parabola, the point of collision P, and the elliptical orbit after collision.

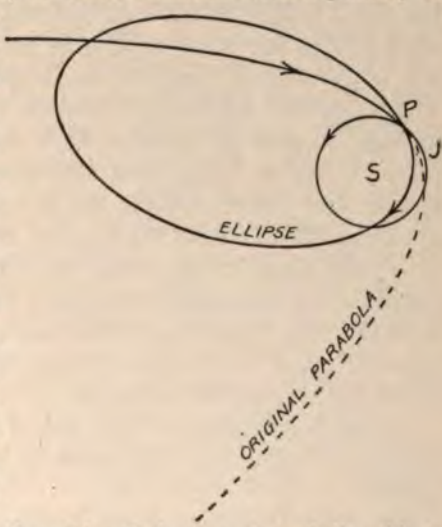


FIG. 186. — Reduction of parabolic orbit to an ellipse by collision of a sun with a planet of another sun.

Now let us follow out the history of the star after such a collision as has been described. If there are no subsequent

working hypothesis. We may then inquire whether there will be luminous stars through infinite time, or whether they all will ultimately become extinct.

According to physical laws as they are known at present, the stars are pouring radiant energy out into the ether at an extravagant rate and it is not being returned to them in relatively appreciable amounts. For example, the sun loses more light and heat by radiation in a second than it will receive from all the stars in the sky in a million years. It is inconceivable that a star has an unlimited store of internal energy. Therefore its energy will ultimately become exhausted unless a new supply is furnished in some way. One method by which the internal energy of a star may be increased is by collision with another star. But after collision the combined mass would lose its energy similarly until another restoration by another collision. But by this process the matter of the universe becomes aggregated in larger and larger masses, and if it is finite in amount, a stage will be reached when no more collisions will take place. Then these final stars will in the course of time radiate away all their internal energy and remain throughout eternity dark, cold, and lifeless. At least, such is the teaching of present-day science if the physical universe is finite, as has usually been assumed.

But now suppose that there are myriads of galaxies composing larger and still larger cosmic units, and remember that there are no observational facts whatever which contradict this hypothesis. Under this assumption the energy in the universe is also infinite. It does not follow from this, however, that it will last an infinite time, for there are, by hypothesis, infinitely many bodies which are subject to collisions and which are radiating energy into the ether. But, on the other hand, if the relative speed of the larger cosmic units is great enough, there will be enough energy to last the infinite universe an infinite time. This follows from the fact that infinities may be of different orders, as the



FIG. 187. — Irregular nebula in Cygnus (N. G. C. 6960). *Photographed by Ritchey with the two-foot reflector of the Yerkes Observatory.*

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our own Galaxy of a higher order than the
l velocities, in harmony with the suggestion

recently brought forward strong evidence
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certainly a hundred years are required for light to cross them. They are extremely faint (the long-exposure photographs being quite misleading) and they are probably very tenuous, though nothing is actually known regarding their density. If they are condensing under gravitation, the process must be going on extremely slowly.

An example of a less widely extended and apparently much denser nebula is the great nebula in Orion (Fig. 61), which is, perhaps, the most wonderful and beautiful object in the heavens. It fills a space whose apparent diameter is more than half a degree. This means it is of enormous volume, for it is as remote as certain stars which are associated with its denser parts. Its parallax can scarcely be over 0″.01 and it probably is much smaller; if the larger value is correct, its diameter is 20,000,000 times that of the sun and several years would be required for light to travel from one side of it to the other. The density of the Orion nebula is altogether unknown, but it is generally regarded as being very low. If it averages even $\frac{1}{100,000}$ that of the atmosphere and if it is spherical (?), its total mass is 100,000,000,000,000 times that of the sun, and in spite of its enormous distance, its attraction for the earth is one fourth that of the sun. If the nebula is rare, it is difficult to account for its radiation, because it could not have a high temperature except possibly in its deep interior where pressure of the outlying parts would prevent expansion. The luminosity of the nebulæ, like that of the comets, has long been an unexplained phenomenon.

The form of the Orion nebula suggests whirling motions of its parts. Relative internal motions were found first by Bourget, Fabry, and Buisson; Frost and Maney have shown by the spectroscope that its northeastern part is receding from the solar system, while the southwestern part is approaching at the relative rate of about 6 miles per second. It is clear that unless the density is sufficiently great these motions will cause the nebula to dissipate in space. On the

assumption that this is simply a motion of rotation, and neglecting gaseous expansion, it is found that the nebula is in no danger of disrupting if its average density is greater than 10^{-22} times that of water. At this limiting density its total mass would about equal that of the sun.

It was supposed in the days of Sir William Herschel that the nebulæ may be galaxies which are so remote that their individual stars are not distinguishable, even with the most powerful telescopes. This is certainly not the true explanation of the irregular nebulæ. In the first place, the spectra of the brighter ones for which the data are at hand consist of bright lines, proving on the basis of the first law of spectrum analysis that they are incandescent gases under low pressure. The bright lines belong to a hypothetical element nebulium, found only in nebulæ, and to hydrogen. In the second place, they are condensed in the zone of the Milky Way, which indicates they are in some way connected with it. Campbell and Moore have found that they show the streaming tendencies which are characteristic of the stars. For these reasons the conclusion is held that they are tenuous gaseous members of our own Galaxy.

A very interesting fact has recently been discovered in connection with the Magellanic Clouds, two masses of stars in the far southern heavens, having the appearance of two smaller galaxies which are quite independent of the Milky Way. R. E. Wilson, at the South American branch of the Lick Observatory, has found that the radial velocities of the nebulæ in the Magellanic clouds which are bright enough for measurement show rapid recession of all of these objects, the average speed being over 150 miles per second. This suggests that these aggregations of stars have velocities with respect to our own Galaxy of a higher order than the average internal velocities, in harmony with the suggestion in Art. 300.

Barnard has recently brought forward strong evidence for the conclusion that there are relatively dark and opaque

The spiral nebulæ are further characterized by being white, whereas the large irregular nebulæ have a greenish tinge due to the green light from nebulium. Most of them are too faint for detailed spectroscopic study, but some of the brighter of them have been found to have spectra similar to the sun's spectrum. This leads to the inference that they are perhaps partly solid or liquid. On the other hand, Seares has photographed some of them through a screen which cuts off the blue end of the spectrum. The brightness of the arms was much more reduced than that of the central nuclei, indicating that a considerable part of their light is similar to that from gases. Moreover, their transparency implies that they are tenuous. Hence, they seem to be vast swarms of incandescent solid or liquid particles, perhaps with many larger masses, surrounded by gaseous materials. There is difficulty in explaining their luminosity, though Lockyer attempted to account for the light of all nebulæ by ascribing it to heat generated by the collisions of meteorites of which he supposed they are largely composed. The obscure material in and around nebulæ may be very abundant. This supposition is confirmed in the case of spiral nebulæ, for when one is seen edgewise the dark



FIG. 189.—The Trifid Nebula. The dark lanes by which it is crossed are probably due to intervening dark material. *Photographed with the Crossley reflector of the Lick Observatory.*

distant as the nearest stars, its volume is enormous; the smallest ones may be as small as the solar system, though they would wind up and lose their spiral characteristics in a short time.

The suggestion has been made (Art. 249) that a spiral nebula may develop when a star is visited closely by another star, or when a group of stars passes near another group of stars. There is no apparent difficulty in explaining small spirals in this way, but the large ones present a more serious problem, especially if we limit ourselves to the close approach of two single stars. It is not at all necessary to do this, for in a general way the dynamical principles involved apply to aggregates of all dimensions up to galaxies, and even beyond if there are larger units in the universe. There is possibly some evidence that the Milky Way has a spiral structure.



FIG. 191. — Spiral nebula in Andromeda (H. V. 19) presenting edge toward the earth. Central line eclipsed by obscure material. *Photographed with the Crossley reflector of the Lick Observatory.*

Although the larger spirals are enormous in extent, they may have only moderate masses. However improbable this may be on the basis of their appearance, it must be remembered that there is no direct evidence whatever at present regarding their masses, and the source of their luminosity is quite unknown. It is natural to suppose that though a spiral of dimensions comparable to the solar system might be produced by the disruptive forces of a near approach of two stars, it would not be possible for one a thousand times larger to be formed in the same way. An examination of the equations involved shows that, if a certain

velocity of ejection would cause matter to recede (neglecting the attraction of the passing sun) to the distance of Neptune, a velocity one twenty-four-thousandth greater would cause it to recede 1000 times farther (Table XIII). Hence the argument against very large spirals being formed by the near approach of two great suns is not so conclusive as it might at first seem. They may have been formed, however, by the passage near one another of two great groups of stars such as the globular clusters; or they may have been formed in some other way not yet considered.

The spectra of spiral nebulæ are in harmony with the suggested mode of their origin. Their distribution demands consideration. Their apparent distribution may mean that they are out on the borders of the Galaxy and that they are not seen in the Milky Way because of their great distances in these directions. It would be expected that close approaches would occur most frequently in the interior of the Galaxy where the stars move the fastest if they are making excursions to and fro through it. On the other hand, out on the borders they would move more slowly and their mutual attractions would be more efficient in bringing them together.

There is one fact which is opposed to the suggested explanation of spiral nebulæ, and that is, as Slipher first found, their radial velocities average very great. For example, the Great Andromeda Nebula is approaching the solar system at the rate of 200 miles per second. Moreover, Slipher found spectroscopic evidence that it is rotating. Even if the result is in doubt for this nebula, it is altogether certain in the case of another spiral which is edgewise to the earth, and which Slipher investigated in 1913. Among the stars high velocities are on the whole associated with small masses. If this is a universal principle, which seems dynamically sound, the spirals must have smaller masses than any known class of stars. Or, perhaps, spirals have been formed on the whole only from stars which passed one another at great



FIG. 192. — Great Nebula in Andromeda. *Photographed by Ritchey with the two-foot reflector of the Yerkes Observatory.*

speed, and they of course still possess most of their kinetic energy.

It has been more than once suggested that the spiral nebulæ are not in reality nebulæ at all, but distant galaxies. If this is true, it is difficult to explain their distribution with respect to the Milky Way, or their strong central condensations, or the fact that they are crossed by dark streaks when they are presented edgewise to us. Besides, the results of Seares' photographs are opposed to this hypothesis.

303. Ring Nebulæ. — A few nebulæ have the form of almost perfect rings, the best example of which is the one between Beta Lyræ and Gamma Lyræ (Fig. 193). This nebula has a fifteenth-magnitude star near its center which has been suspected of being variable. It is probably associated with the nebula, though this is not certain. The spectrum of the ring nebula in Lyra has been examined and it has been found that hydrogen extends out considerably beyond the helium. The origin and development of these remarkable objects are quite beyond conjecture at present.



FIG. 193. — The ring nebula in Lyra. *Photographed by Sullivan at the Yerkes Observatory with the 40-inch telescope.*

304. Planetary Nebulæ. — The planetary nebulæ are supposed to be next to the O-type stars in evolution, and the O-type stars are supposed to precede the B-type stars. They are in all cases apparently small in size, usually rather dense, particularly near their centers, and they have rather well-defined outlines. They were named by Herschel from their resemblance to faint planetary disks.

The spectra of about 75 planetary nebulæ have been examined. Perhaps the most important result of this examination is that their radial velocities (24 miles per second) are

at least three times those of the stars of Type B. This is squarely opposed to the theory that they condense into stars of Types O and B. If this theory is maintained, an explanation of the greatly decreased velocities is demanded, and none is at hand. On the other hand, the novæ go first into planetary nebulæ and then into Wolf-Rayet stars.

The central parts of planetary nebulæ give the lines of nebulium and hydrogen; the outermost parts give the hydrogen lines alone. That is, hydrogen forms an atmosphere around the denser nebulium and hydrogen cores.



FIG. 194. — A planetary nebula. *Photographed with the Crossley reflector at the Lick Observatory.*

The problem of the rotation of planetary nebulæ is now being taken up at a number of observatories. By an adaptation of the spectroscope first employed by Keeler on the rings of Saturn, and used more recently by Slipher at the Lowell Observatory on planets and spiral nebulæ, Campbell and Moore have found that two of these remarkable objects are rotating around axes approximately at right angles to a plane passing through the earth and the longer axes of the nebulæ. On the basis of the observed relative velocities of 3.1 to 3.7 miles per second, and plausible assumptions regarding the distance of the nebulæ, they found that their masses are between 3 and 100 times that of the sun, with periods of rotation between 600 and 14,000 years. With such slow rates of rotation there is no possibility of these objects ever dividing into two parts and forming a binary star, in spite of the fact that their density probably does not exceed one millionth that of our atmosphere at sea level.



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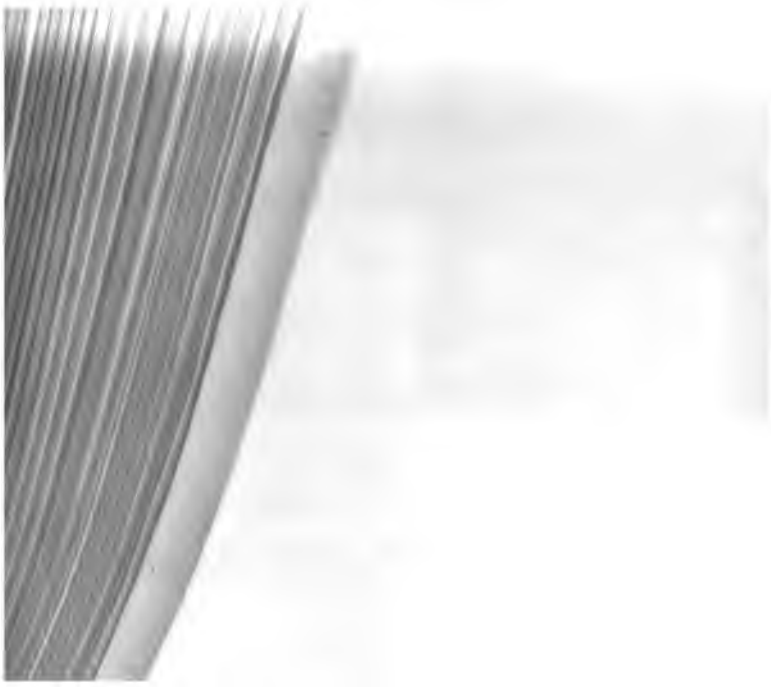
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